Prospects for Low Cost Fusion Development

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14. ABSTRACT

In 2014 ARPA-E initiated the three-year $30M ALPHA program to explore magneto-inertial fusion (MIF) concepts in a span of 10^5 in plasma density (10^{18} – 10^{23} ions/cm^3), lying between the mainline tokamak (10^{14}/cm^3) and inertial (NIF at 10^{26}/cm^3) approaches. ALPHA's goal was to identify ways to accelerate progress toward fusion power.

With the ALPHA program nearing completion, ARPA-E asked JASON to assess its accomplishments and the potential of further investments in this field. JASON members listened to two days of briefings that included participants in ARPA-E's ALPHA program, MIF teams not supported by ALPHA-E, and teams working on pure magnetic confinement fusion. JASON also surveyed nine teams for quantitative metrics of past, present, and projected progress along critical physical parameters.

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Contents

EXECUTIVE SUMMARY

Controlled thermonuclear fusion has been pursued for more than 60 years. In recent decades, US funding has focused on laser-driven inertial confinement (ICF) for national security purposes and on magnetic confinement (MCF), primarily in tokamaks, for energy production. The major component of the latter international program is the $25B ITER project, expected to begin DT operation in 2035.

In 2014 ARPA-E initiated the three-year $30M ALPHA program to explore magneto-inertial fusion (MIF) concepts in a span of 10^5 in plasma density (10^{18} – 10^{23} ions/cm^3), lying between the mainline tokamak (10^{14}/cm^3) and inertial (NIF at 10^{26}/cm^3) approaches. ALPHA's goal was to identify ways to accelerate progress toward fusion power.

With the ALPHA program nearing completion, ARPA-E asked JASON to assess its accomplishments and the potential of further investments in this field. JASON members listened to two days of briefings that included participants in ARPA-E's ALPHA program, MIF teams not supported by ALPHA-E, and teams working on pure magnetic confinement fusion. JASON also surveyed nine teams for quantitative metrics of past, present, and projected progress along critical physical parameters.

The findings of this study are summarized as follows:

1. Magneto-Inertial Fusion (MIF) is a physically plausible approach to studying controlled thermonuclear fusion in a region of parameter space that is less explored than Inertial Confinement Fusion (ICF) or Magnetic Confinement Fusion (MCF).
2. MIF research is immature. Despite having received ~1% the funding of MCF and ICF, MIF experiments have made rapid progress in recent years toward break-even conditions, and some (e.g. MagLIF) are within a factor of 10 of 'scientific break-even'.
3. There are many plausible and distinct approaches to MIF. Some early projects supported by the ALPHA program are showing rapid progress in critical physical parameters and have not *yet* reached insurmountable obstacles. As in ICF and MCF, instabilities may make scientific break-even MIF more challenging than simple scaling estimates suggest.
4. ALPHA program support for development of broadly applicable technologies has accelerated progress of multiple efforts. All MIF approaches would benefit from improved understanding of plasma instabilities and liner-plasma interactions, better computational tools, and improved diagnostics.
5. While scaling from current experiments is uncertain, it is likely that reaching scientific break-even with a single MIF prototype will cost at least several $100M and possibly much more. Considerably larger expenditures would be required to go from scientific breakeven to a demonstration power plant; and even more from a demo to a production capability.
6. Given the immaturity of the technologies, the future ability of fusion-generated electricity to meet commercial constraints cannot be usefully assessed. Rapidly developing infrastructures for natural gas and renewable energy sources and storage will compete with any future commercial fusion efforts. Nevertheless, there is a small but growing private-sector community investing in and pursuing commercial fusion projects.
7. The pursuit of MIF could lead to valuable spinoff technologies, and to non-power fusion applications, with broad civilian and military import. Some approaches have low enough mass to be candidates for space propulsion, but it is too early to impose the relevant design constraints (low weight, low thermal dissipation) on ongoing research.

8. MIF research could productively absorb a significantly higher level of funding than the $10M/yr of the ALPHA program.

These findings lead to the following recommendations:

1. MIF activities should be supported by an investment in basic research to:
    - study plasma instabilities and transport under MIF conditions, and
    - study plasma-liner interactions.
2. The National Laboratories should contribute their unclassified state-of-the-art simulation codes to collaborations with academic and commercial efforts, and support training of qualified users.
3. Targeted technology development programs should focus on development of components, including plasma guns (high Z and low Z), pulsed power and electronics, diagnostics, and advanced magnets and materials.
4. The near-term goal should be scientific break-even (thermonuclear energy out > mechanical + electromagnetic energy into the fuel) in a system that plausibly scales to a commercial plant. Until that goal is achieved, set aside questions of neutron economy (tritium breeding) or balance of plant. Pursue system integration only insofar as it is needed to demonstrate scientific break-even.
5. Explore pulsed neutron sources and space propulsion as motivating applications with different constraints than grid electricity. Efforts in these speculative directions should supplement, not replace, basic MIF research.
6. Support all promising approaches for as long as possible. Do not concentrate all resources on early front-runners.

1 INTRODUCTION

This document reports on an ARPA-E-sponsored JASON assessment of the “Prospects for Low Cost Fusion Development.” Specifically, the question is whether magneto-inertial fusion (MIF) is a promising approach toward achieving controlled thermonuclear fusion at dramatically lower costs than other approaches. MIF operates at ion densities from 10^{18} – 10^{23} ions/cm^3, part-way between the main-line approaches of Magnetic Confinement Fusion (MCF, 10^{14} ions/cm^3) and Inertial Confinement Fusion (ICF, 10^{26} ions/cm^3). MIF techniques combine aspects of the two main-line approaches: magnetic fields are used to suppress cross-field particle and heat transport, as in MCF. Impulsive mechanical compression is used to reach high density and temperature, as in ICF. If MIF research is found to be promising, how can the government best support progress?

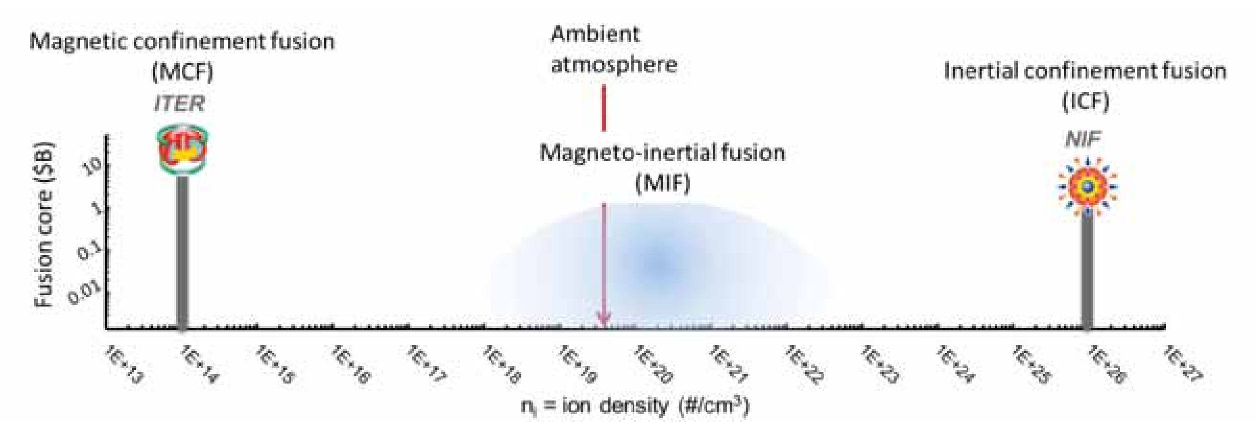

Figure 1. Fusion landscape. Magneto-inertial fusion resides at an intermediate density between Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF). Image adapted from P. McGrath, ARPA-E.

In 2014 the Advanced Research Projects Agency-Energy (ARPA-E) initiated a program on Accelerating Low-cost Plasma Heating and Assembly (ALPHA) to support MIF research. Between 2015 and 2018 the program disbursed $30M in grants to 9 teams. As the ALPHA program ends, ARPA-E and the federal government must decide how to build upon the initial efforts.

Some of the key questions are:

1. What areas of MIF research show promise of reaching scientific break-even?
2. What are the key technical and schedule risks?
3. What areas of investment or support would best accelerate further progress toward MIF scientific break-even?

The complete Statement of Work is given in Appendix A.

Our study was informed by an extensive collection of public documents, as well as two days of briefings from a broad range of stakeholders, including ARPA-E and NASA, the private sector, and universities (Appendix B). In addition, we surveyed teams working on MIF projects to gather quantitative metrics on progress and plans, and to gather community input on the key remaining challenges (Appendix C).

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2 CONTEXT

For a fusion reaction to provide useful energy, the energy released by the reaction must exceed the mechanical and electromagnetic energy supplied to assemble the reactants. This condition is called 'scientific break-even', and the ratio of energy out to energy in is called 'scientific gain'. Even with a charitable definition of "energy in", that condition was only recently approached in an ICF experiment at the National Ignition Facility (NIF) in Summer 2018[1], but that system does not lie on a route to a practical fusion reactor.

Scientific break-even is necessary, but not sufficient, to produce a functioning fusion power plant. There are additional energy losses associated with the energy conversions upstream of fuel assembly and downstream of the fusion reaction (Figure 2). For power plant gain (electrical energy out/electrical energy in) to exceed one, the scientific gain must exceed ~10. In this report, we focus primarily on the challenge of finding a path to scientific gain > 1 in a high repetition-rate platform, as the proximate challenge along the path toward fusion as a practical energy source.

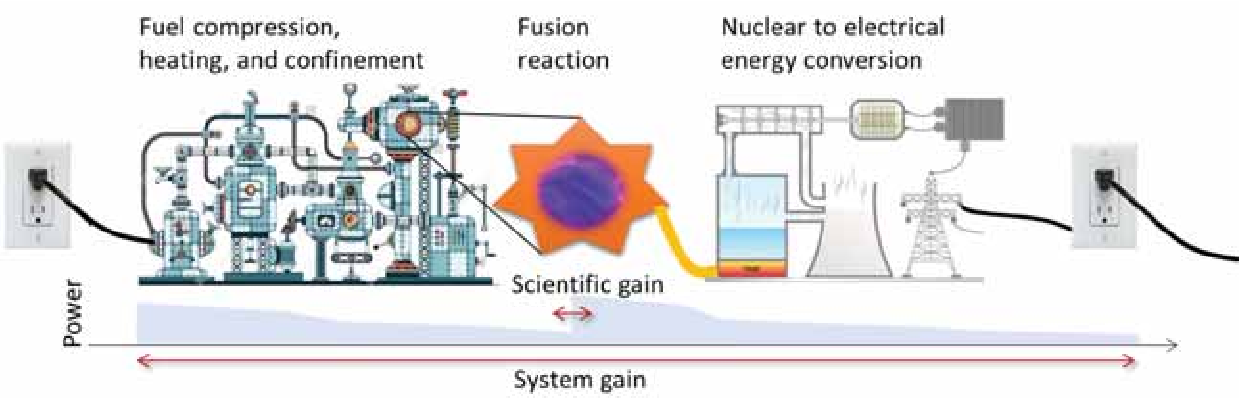

Figure 2. Energy flow in a fusion reactor. This notional diagram of a fusion power plant shows an apparatus that draws electrical energy from the grid, and through a series of transformations compresses, heats, and confines a fusion fuel. Some energy is converted to waste heat during each step. The fusion fuel reacts, releasing high-energy nuclear products. The energy from these products is converted to electrical energy with thermodynamically limited efficiency. The salable electricity is the difference between the electricity produced and the electricity that must be recycled to operate the plant.

The physical requirements for scientific break-even are that the fuel must be sufficiently hot, dense, and confined for long enough. For the most promising fuel, an equimolar deuterium-tritium (D-T) mixture near its optimal ion temperature of about 14 keV, these requirements are captured by the so-called 'triple product' $n\,T\,\tau$, where n is the density of ions, T is the ion temperature, and τ is a measure of the energy confinement time (discussed in detail below). Then the scientific break-even condition is:

$$n\,T\,\tau \approx 3 \times 10^{21}\ \mathrm{keV\ s/m^3},$$

[1] S. Le Pape, et al., "Fusion energy output greater than the kinetic energy of an imploding shell at the National Ignition Facility." *Physical Review Letters* **120,** 245003 (2018).

where temperature is measured in keV (1 keV = 1.2×10^7 K), time in seconds, and density in ions/m^3. One can go to higher density for shorter time, or lower density for longer time—but any combination of these parameters that crosses the scientific break-even condition has proven extraordinarily difficult to achieve under controlled conditions. At ion temperatures below 10 keV the condition on the density-time product is much more demanding; T must approach 10 keV to be "in the ballgame" at all.

2.1 The Space between ITER and NIF

At present, there are two main approaches toward achieving controlled thermonuclear fusion. In Magnetic Confinement Fusion (MCF), a hot plasma is kept away from the reactor walls by a confining magnetic field. Although many geometries of MCF devices have been explored, the most common geometry today is the tokamak, a toroidal configuration with a predominantly toroidal magnetic field. Tokamaks typically operate at an ion density of ~10^{14}/cm^3.

The flagship tokamak program is the international collaboration on ITER, under construction in France. It is projected to cost approximately $25B, more than twice the initial budget, and to commence D-T fusion operation around the year 2035, more than a decade behind the original schedule. The Department of Energy (DOE) Office of Fusion Energy Sciences (OFES) budget is $564M (2019) for plasma fusion research, of which $432M is for domestic research and $132M goes to ITER.[2,3]

The second main approach to controlled fusion is Inertial Confinement Fusion (ICF), in which a millimeter-size capsule is compressed via an intense laser pulse to a density of ~10^{26}/cm^3, corresponding to ~300 times the density of water. In the US, ICF research is focused at the National Ignition Facility (NIF) at Lawrence Livermore National Lab. Controlled fusion experiments at NIF recently passed the milestone of producing thermonuclear energy (54 kJ) greater than the mechanical kinetic energy in the imploding liner (21 kJ). This energy output is still far smaller than the optical energy used to compress the shell (1.5 MJ), and the NIF is not considered as a prototype for a future power plant. The NIF program total cost has been approximately $3.3B, and is sponsored by the National Nuclear Security Administration (NNSA) within the DOE. The mission of NIF is primarily national security (stockpile stewardship), with ICF only one of several programs at the facility. The total budget for the Inertial Confinement Fusion and High Yield program is $545M (2019) of which $344M is for NIF.[4] Of the NIF budget, approximately $80M is for ignition research. In 2013 the National Research Council produced a detailed study of the prospects for ICF energy production.[5]

The two mainline approaches, MCF and ICF, are dramatically different in many ways. Apart from a factor of ~10^{12} in maximal fuel density, they also differ in timescale: MCF systems operate quasi-statically, with runs lasting from tens of seconds to minutes, while ICF operates in a pulsed mode, with maximal compression lasting ~150 ps.[6] MCF is performed in the presence of a strong magnetic field (5.3

[2] https://aries.pppl.gov/FPA/fpn18-38.shtml
[3] https://science.energy.gov/~/media/budget/pdf/sc-budget-request-to-congress/fy-2019/FY_2019_SC_FES_Cong_Budget.pdf
[4] https://aries.pppl.gov/FPA/fpn18-38.shtml
[5] National Research Council. An Assessment of the Prospects for Inertial Fusion Energy. National Academies Press, 2013.
[6] S. Le Pape, et al. "Fusion energy output greater than the kinetic energy of an imploding shell at the National Ignition Facility." *Physical Review Letters* **120**, 245003 (2018)

T at ITER), while ICF is performed without externally applied fields. The fuel chamber for MCF is a substantial portion of the device--at ITER, the reaction chamber torus is 6.5 m in inner cross-sectional width. In ICF the fuel is a small pellet ~1 mm in diameter, the evacuated "target chamber" is 10 m in diameter, and the rest of the apparatus is the size of three football fields.

Despite the dramatic differences in physical parameters, MCF and ICF have two features in common: they are extremely expensive, and they have not yet "worked", in the sense of reaching scientific break-even. Why are the systems so expensive? To a zeroth approximation, it is because they are very large. Why are they so large? In MCF the torus must be large enough that losses at the surface do not dissipate heat faster than fusion reactions can replenish the heat in the bulk. Thus surface-to-volume arguments set the size. In ICF, the target is tiny, and the size of the machine is dominated by the laser required to precisely deliver the compressive impulse of ~2 MJ in 7.5 ns (momentarily exceeding worldwide primary power consumption).

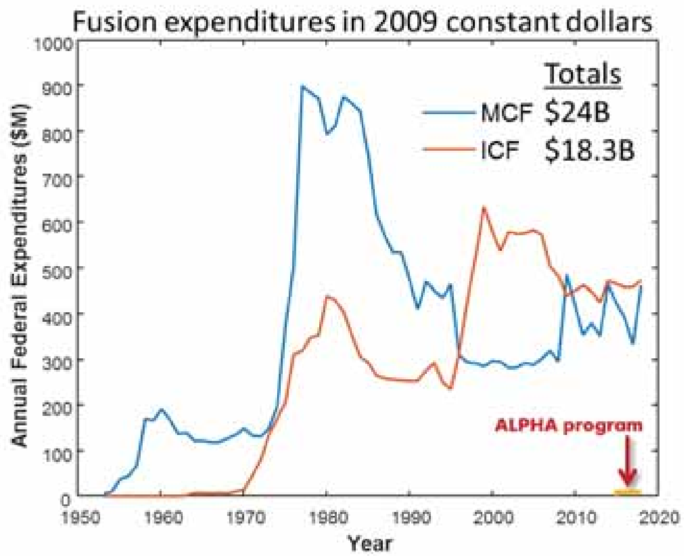

Figure 3. US government expenditures on fusion research. ALPHA expenditure on MIF research was $30M ($26M in 2009 constant dollars). Data from: https://aries.pppl.gov/FPA/OFESbudget.html

The existence of physically plausible, but technically challenging, approaches to controlled fusion at densities differing by a factor of ~10^{12} raises the question: are there other viable approaches at intermediate densities? If so, might they be less technically demanding, and hence less expensive?

Fig. 3 shows US expenditures on fusion research. Of the ICF budget, approximately 15% is directed toward ignition research.[7] The cumulative ALPHA program to explore magneto-inertial fusion (MIF) had a total budget of $30M.[8] Earlier DOE expenditures on MIF were of comparable magnitude. This graph is the basis for **Finding 2: MIF research is immature, as it has received ~1% the funding of MCF and ICF.**

2.2 A Brief History of 'Alternative' Approaches

Nuclear fusion research has a long history. It was hypothesized as the energy source of stars in the 1920's; that fusion reactions produced energy was demonstrated in the laboratory in the 1930's; it was largely put aside, but not forgotten, during World War II; fission-driven uncontrolled fusion reactions were demonstrated by the so-called "hydrogen bomb" in 1952 by the United States; and efforts to produce controlled fusion reactions in the laboratory began in earnest in the US, the UK and the USSR in the early 1950's. Unfortunately, controlled fusion at the level of energy break-even remains elusive.

[7] https://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_088736.pptx
[8] https://aries.pppl.gov/FPA/OFESbudget.html

In contrast, the development of nuclear fission was amazingly rapid. After its startling discovery in 1938, nuclear reactors using neutron-induced fission chain reactions began operating four years later, nuclear fission weapons arrived after three more years, and the first nuclear power plants appeared during the 1950s.

Why is fusion so much harder than fission? The principal problem is that a fusion reaction involves two positively charged low atomic number atomic nuclei that come together and "fuse" despite their electrostatic ("Coulomb") repulsion, requiring the nuclei to approach each other with very high relative velocity. By contrast, fission involves reactions between a neutral particle—a neutron—and heavy atomic nuclei. Thanks to the lack of Coulomb repulsion, some heavy nuclei (called "fissile" nuclei) are so susceptible to fission reactions that a low energy ("room temperature") neutron can induce the reaction, driven by the binding energy of the added neutron—not by the kinetic energy of the neutron. Since the fissions release more neutrons, a chain reaction can be produced and sustained in a reactor by assembly of a "critical mass", i.e., enough fissile nuclei to sustain the reaction chain despite losses from the finite reactor volume. Fusion, by contrast, requires assembly of a certain mass of fuel, heating it to high temperatures (> 10^7 K so as to have high relative energies when the nuclei collide), and maintaining it at adequate density to have enough fusion reactions occur that the original input energy investment is recovered.

The hydrogen bomb demonstrated fission-driven, uncontrolled "inertial confinement fusion" (ICF) in 1952, so named because no confinement method other than the physical size and the inertia of the hot fuel was used to confine it. A *laser-driven* controlled ICF program was initiated in the US soon after the pulsed laser was invented in 1960.[9][10] Likewise, the magnetic confinement fusion (MCF) programs addressing controlled fusion in the US, the UK and the USSR were initiated in secrecy. In the US, this was because they were "born classified" according to the Atomic Energy Act of 1954[11]. Recognizing the difficulty of achieving MCF early on, first the USSR and then the UK and the US, declassified MCF research in the late 1950's and scientists in other countries began such research. Most MCF configurations that are being considered today were already conceived by 1960, including tokamaks, stellarators, z-pinches and field-reversed configurations.[12] Inertial Confinement Fusion research in the US was partially declassified in the 1970s (direct-drive ICF) and fully declassified in 1994.

Initially, researchers in ICF hoped that tightly focused laser beams at total energies far less than 1 MJ could trigger fusion by imploding tiny fuel capsules; however experiments showed that laser energy deposition became highly inefficient due to laser-plasma instabilities, which reflected most of the incident energy backwards, and hot electron generation, which preheated the fuel and reduced achievable density. Controlling these effects required larger capsules and more powerful lasers at shorter wavelengths. Later it was found that hydrodynamic instabilities hindered capsules from imploding to high convergence ratios, requiring still more powerful lasers. This led to the construction of the National Ignition Facility (NIF), a 1.8 MJ (at 351 nm wavelength), 192-beam laser facility at the Lawrence Livermore

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[9] J. H. Nuckolls, "Early Steps Toward Inertial Confinement Fusion Energy (IFE) (1952 to 1962)", UCRL-ID-131075, LLNL (1998).

[10] T. H. Maiman, "Stimulated Optical Radiation in Ruby," *Nature* **187**, 494 (1960).

[11] https://www.nrc.gov/about-nrc/governing-laws.html#aea-1954

[12] http://www-fusion-magnetique.cea.fr/gb/fusion/histoire/site_historique.htm

National Laboratory. Progress toward ignition, operationally defined as achieving 1 MJ or more fusion yield, continues to be challenged by hydrodynamic instabilities and other non-linear physics phenomena involving the intense laser beams inside the indirect drive target. Only recently have laser shots on the NIF produced fusion energy greater than the kinetic energy in the imploding capsule (and still far less than the electromagnetic energy in the laser beam).[13]

In the 1970s, national and international MCF programs were also optimistic that a commercially viable fusion reactor could be designed and built by the year 2000, despite unexplained deficits in the energy and particle confinement times. The leading device at the time for pursuing scientific breakeven in the 1970s was the tokamak, which led a majority of MCF program funding to be allocated to tokamaks in the 1980s. Alternative concepts were eliminated, despite widespread contemporaneous arguments that field-reversed configurations (FRCs) or devices called spheromaks could be more commercially viable reactors than tokamaks if confinement and heating issues could be solved.

Over the past 30 years, considerable theoretical, computational and experimental efforts have identified the instabilities that limited confinement in tokamaks. Through experience with many tokamak designs, the MCF community developed empirical scaling relationships that predicted that achieving scientific break-even with the magnet technology of the mid-1990s would require an ITER-sized machine. While most MCF resources worldwide shifted to ITER, subsequent developments in high-T_C superconducting magnet technology raised hopes that a high-field Tokamak much smaller than ITER might achieve scientific break-even in a shorter time and at lower cost.[14] The question of commercial viability of a tokamak as a fusion reactor remains.

Thus, in recent years, alternative approaches to MCF that might enable lower cost development are being pursued, many of which involve the compact toroid configuration, i.e. a toroidal plasma that does not require a magnetic coil running through its center. The Spheromak and the field-reversed configuration (FRC) are two special cases of the compact toroid. Most of these projects are privately funded.

In the 1940's, Fermi in the U.S. and Sakharov in the Soviet Union independently realized that a magnetic field could reduce cross-field losses of particles and energy in a fusion plasma.[15] Research on magneto-inertial fusion (MIF) proceeded independently in the two countries until the end of the Cold War. In the West, Linhart and coworkers performed the first MIF experiments in 1962, identifying many of the key concepts that persist to this day.[16] At the end of the Cold War, Russian and American researchers compared achievements, and a Russian approach called MAGO emerged as the most

[13] S. Le Pape, et al., "Fusion energy output greater than the kinetic energy of an imploding shell at the National Ignition Facility." *Physical Review Letters* **120**, 245003 (2018).

[14] Greenwald, M., et al. "The High-Field Path to Practical Fusion Energy." http://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_185099.pdf

[15] I. R. Lindemuth, et al., "Magnetic-Compression/Magnetized-Target Fusion (MAGO/MTF): A marriage of inertial and magnetic confinement." No. LA-UR-96-3939; CONF-961005-14. Los Alamos National Lab., (1996).

[16] J. G. Linhart, et al., "Amplification of magnetic fields and heating of plasma by a collapsing metallic shell." Euratom-CNEN, Frascati, Italy, 1962.

advanced alternative project[17,18] at least by the criterion of neutron production. MAGO involved compression of a magnetized plasma by a collapsing metal liner, similar in concept to the ongoing MagLIF project at Sandia.

Figure 4 shows a taxonomy of approaches to controlled thermonuclear fusion. The overall impression is that many diverse approaches have been tried. None has succeeded (yet), but few have been conclusively ruled unworkable. The present study is restricted to thermonuclear approaches; *i.e.*, where the distribution of ion velocities is (approximately) governed by a Maxwell-Boltzmann distribution with a well-defined temperature. Even within the MIF domain, there is a wide diversity of approaches, as we will explore below.

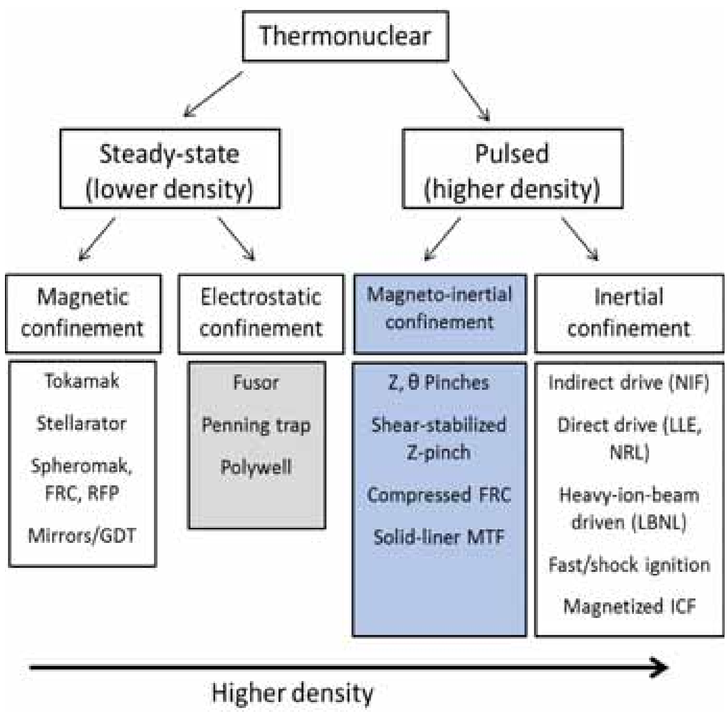

Figure 4. Approaches to controlled fusion. Thermonuclear approaches maintain an approximately Maxwell-Boltzmann velocity distribution, permitting each ion to undergo many Coulomb scattering events prior to a fusion reaction. MIF approaches are shaded in blue. Approaches unlikely to reach scientific break-even are shaded in grey. Image adapted from S. Hsu, LANL.

We also note the possibility of non-thermal approaches, wherein the kinetic energy does not follow a Boltzmann distribution. These assume a strongly anisotropic ion velocity distribution. Beams readily put most of the input energy into the reaction coordinate. The challenge is that un-productive collisions (Coulomb scattering) randomize the velocity vectors, quickly evolving the system toward thermal equilibrium. The goal is to attain a high enough rate of productive collisions to compensate for the wasted input energy from elastic scattering and bremsstrahlung losses. Whether such a goal is

[17] I. R. Lindemuth, *et al*., "Target Plasma Formation for Magnetic Compression/Magnetized Target Fusion", *Physical Review Letters* **75**, 1953 (1995).

[18] P. Sheehey, *et al.*,"Computational and Experimental Investigation of Magnetized Target Fusion", CONF-9606116—56, LANL (1996), and references cited therein.

attainable has been the subject of debate[19,20,21] One large-scale commercial effort (TAE) uses non-thermal ions.

Although peaceful energy production is the most prominent stated goal of alternative fusion projects, arms control experts have pointed to conceivable military applications of pure fusion, such as small-yield weapons[22]. In a 1998 declassification decision, the U.S. DOE stated that "the U.S. does not have and is not developing a pure fusion weapon and no credible design for a pure fusion weapon resulted from the DOE investment".[23] The Comprehensive Nuclear-Test-Ban Treaty, which bans "nuclear explosions", does not specifically address pure fusion. The U.S. has signed but not ratified that treaty, yet observes its provisions; the US position is that ICF is allowed. If fusion power is eventually achieved, the arms-control implications will be non-negligible but likely manageable to an extent similar to that of fission power through the IAEA and international treaties.[24]

2.3 Fusion in the Energy Landscape

Fusion energy has long held a special mystique in science and in popular culture as a technology that would be utterly transformative, if only it could be made to work. The prospect of a virtually inexhaustible fuel source was especially compelling in the 1950s to '70s after the finiteness of fossil fuels had been recognized (either through finite supply or the deleterious effects of combustion). This motivation declined with revised estimates of fossil fuel and uranium reserves, which have increased dramatically over earlier estimates; and declined further with the emergence of affordable and inexhaustible renewable resources.

Today's strategic outlook is not defined by fuel scarcity, but by overall system cost, environmental impact, and operational constraints that limit a technology's ability to produce on a flexible schedule that meets electricity demand. There is no fundamental shortage of primary energy resources to motivate the development of fusion *per se*. Moreover, existing technologies can meet demand with substantial margins, and a mixture of technologies can be dispatched according to their economic merit to reduce the system cost to below that of any individual technology.

For fusion energy to become commercially viable and relevant in the current context, fusion must not only work within this system, but it must be better than some existing technology in one or more dimensions. Those dimensions include the effective levelized cost of generation (present value of the total cost of building and operating a power plant over an assumed lifetime and duty factor, divided by energy

[19] T. H. Rider, "Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium." *Physics of Plasmas* **4**, 1039-1046 (1997).

[20] N. Rostoker, A. Qerushi, and M. Binderbauer. "Colliding beam fusion reactors." *Journal of Fusion Energy* **22**, 83-92 (2003).

[21] N. Rostoker, M. W. Binderbauer, and H. J. Monkhorst. "Colliding beam fusion reactor." *Science* **278,** 1419-1422 (1997).

[22] S. L. Jones and F. von Hippel, "The Question of Pure Fusion Explosions under the CTBT" *(pdf). Science and Global Security 7: 129–150.* (1998) doi:10.1080/08929889808426452.

[23] Department of Energy, "RESTRICTED DATA DECLASSIFICATION DECISIONS, 1946 TO THE PRESENT (RDD-8) " page 90, https://fas.org/sgp/othergov/doe/rdd-8.pdf (2002).

[24] National Academies, **Assessment of Inertial Confinement Fusion Targets**, chapter 3 (2013).

production), operational flexibility, environmental and proliferation impact, and non-technical factors such as public acceptance, aesthetics, or prestige.

The U.S. Grid Context: Assuming the main product of fusion reactors to be electric, not thermal, energy (which other studies have assessed to be a good assumption[25]), their economics must be considered in the context of electric grid operations and electricity markets. This context is rapidly evolving; the character of the U.S. grid by the time commercial fusion reactors could come online is open to broad speculation, and will be influenced by yet-to-be-made regulatory decisions. Segmented grids with a predominance of local generation, storage and controllable loads, which could render large baseload generators obsolete even if they provide bulk energy at lowest cost, are not out of the question. As of 2018, conventional coal plants are becoming uneconomical to operate and new nuclear plants are becoming uneconomical to construct in the face of competition from natural gas generation that is both inexpensive and highly flexible.

Some designers of next-generation fission reactors now favor smaller, more modular and flexible units in the hope that factory manufacture might reduce the cost of construction through economies of scale, and lower finance rates (arising from a lower fraction of the utility's total capitalization being at risk) will reduce the cost of financing reactors. The success of this strategy remains to be shown, however, and it is too early to say whether a similar strategy could be adopted for fusion.

As energy production includes a greater component of intermittent renewable resources, such grid-specific qualities of generation as dispatchability, ramp rates, and response times are becoming increasingly valuable properties, enabling technologies to compete on terms that go beyond cost per kilowatt-hour. For example, generators sell grid services such as load following or frequency regulation that require them to vary their power output at specific rates (on the order of MW per minute) and with specific response times (on the order of seconds to minutes), where the revenue from these ancillary services can match or even exceed the profit from energy sales in certain specialized markets.[26] Simply put, flexibility of operation matters. Flexibility favors technologies with low capital investment, so that costs can be decreased when demand is low.

In the United States, natural gas is by a significant margin the lowest cost way to accommodate the intermittency of renewable generation, followed by electricity storage. The role of natural gas may eventually have to decrease, however, if carbon-abatement policies are successful in bringing emissions to well below 50% of current levels.[27] In such a world, there may be opportunities for fission and fusion to compete with storage for offsetting intermittency. Under a scenario that forbids carbon emission from natural gas, higher prices may have to be tolerated as a matter of policy, permitting fission and fusion technologies to enter the market even at currently speculated prices. Nevertheless, this means that even

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[25] MIT Energy Initiative, *The Future of Nuclear Energy in a Carbon-Constrained World,* September 2018. pp. 27, 75ff, and Appendix F.

[26] B. Kirby, *Ancillary Services: Technical and Commercial Insights*. White Paper prepared for Wärtsilä, 2007. http://www.consultkirby.com/files/Ancillary_Services_-_Technical_And_Commercial_Insights_EXT_.pdf (accessed Sep 6, 2018).

[27] *National Security Implications of the U.S. Nuclear Industry and its Position in the Global Market,* JASON Technical Report, JSR-17-07, Appendix B (2018).

if all scientific and engineering challenges are overcome and fusion reactors can be built at projected costs, their business case will ultimately depend on climate-policy choices that have yet to be negotiated in the U.S. political system.

In 2017, the wholesale electricity price in the United States was \$34/MWh, or \$0.034/kWh. This reflects the average marginal cost of production (influenced by tax credits and other factors) and favors existing production technologies with the lowest absolute marginal cost. This is not a good estimate for new construction, however, as capital costs influence investment decisions. A better long-term forecast may be had by considering the projected levelized cost of new generation with which fusion must compete. Table 1 gives the U.S. Energy Information Administration's forecast for the levelized costs of generation resources entering service in 2040, suggesting a wholesale price of approximately \$0.05/kWh, assuming no stringent constraints on CO_2 emissions.

Fusion energy at 5¢/kWh? Let us consider a world in which \$0.05/kWh is the maximum price that a future fusion plant will be able to charge for grid electricity (with the caveats that regulatory decisions may increase this number; and there may be geographic locations or special circumstances in which the value of electricity is much higher). We can estimate maximum costs for a viable plant as that where revenue just covers the plant's construction costs, interest, fixed operating cost, fuel, maintenance, and waste disposal fees. We shall see that even with reasonably optimistic assumptions on the engineering, the economics will be challenging.

Table 1. Levelized cost estimate for electricity generation resources entering service in 2040 (2017 dollars). Numbers reflect wholesale capacity-weighted average prices without tax credits. Nuclear estimate is for 2022 (no 2040 estimate available) Source: Tables B1 and 1b of https://www.eia.gov/outlooks/aeo/pdf/

Modality	Levelized cost/kWh electricity (2017 ¢US)
Natural gas combined cycle	5.0
Solar photovoltaic	4.4
Onshore Wind	5.6
Advanced Fission	9.3

The literature on fusion energy generally assumes capital cost for reactor construction as the main driver, expecting intrinsic fuel costs to be negligible. Overnight construction cost (construction cost neglecting financing cost during construction) by itself is insufficient information. Build time and interest are key factors that plant design will attempt to address but cannot entirely control, and overall project costs remain highly vulnerable to delays. Operation and maintenance costs also harbor significant uncertainties. Examples include the periodic replacement of components exposed to high-energy neutrons, and regulatory requirements for handling tritium inventories and low-level waste from activated materials.

Let us consider financing costs alone, since these are easily quantified. The analysis below uses reasonable assumptions based on currently contemplated MIF technologies, and is primarily intended to illustrate that deviations from one or more of these assumptions will be needed to make an economically viable power plant. A 30-year loan at 7% annual interest incurs a financing cost of approximately \$9/hr per \$million (M) of loan. To cover financing alone, a power plant must sell a time-average excess electric power at \$0.05/kWh of at least:

$$P_{electric} > \frac{180\ \mathrm{kW_e}}{\$\mathrm{M\ financing}}$$

or equivalently have overnight capital costs of less than \$5.55/W_e.

Cost of a notional power plant: The ALPHA project sponsored calculation of cost estimates for MIF power plants. The estimates were performed in a collaboration between Bechtel National, Woodruff Scientific, and Decysive Systems (hereafter the `Bechtel Report') and considered reactor cores comprised of four prospective MIF technologies: Stabilized Liner Compressor, Plasma Jet Driven Magneto-Inertial Fusion, Staged Z-Pinch, and Shear Flow Stabilized Z-Pinch.[28] These technologies were also among those briefed to JASON.

For a nominal reactor of 150 MW_e, the Bechtel report estimated plant costs to range from \$0.7 to \$1.93Bn, with a mean estimated overnight capital cost of \$1.32Bn. The authors of the Bechtel report correctly emphasized that these estimates are notional, at best, considering that the underlying physics has not yet been demonstrated in the relevant regimes. Taking these estimates at face value, in the simple JASON financing model above, financing costs alone on \$0.83Bn would consume 100% of the revenue from a 150 MW_e plant that operated at 100% duty cycle.

Here we give a condensed summary of the estimates in the Bechtel report to illustrate the dependence on key parameters. Consider a nominal pulsed fusion reactor constructed at a cost of \$1B, with 500 MJ nuclear yield per shot (at the upper end of the range typically considered for MIF). Typical thermal-to-electrical conversion efficiencies are ~40%, yielding 200 MJ electrical energy (MJ_e) per shot. Some of this energy must be recirculated to power the next shot. Assuming a scientific gain of 20, the 500 MJ nuclear yield will require 25 MJ energy input into the fuel. Assuming conversion of electrical energy into fuel energy at 50% efficiency, we must divert 50 MJ_e to sustain the reaction, i.e. one quarter of the electricity production is recirculated just to keep the plant running. This estimate leaves 150 MJ_e to sell, or 41.4 kWh_e. At \$0.05/kWh_e, this estimate gives \$2.07 of electricity per shot. This fact is known as the 'kopek' problem, a Russian reference to the tiny revenue available from a single fusion shot. If the plant continually produces 1 shot/s, then it will produce 150 MW_e and a revenue of \$7,500/hr. This revenue would be insufficient to cover the financing costs of \$9,000/hr.

The hypothetical Bechtel-like plant has an overnight capital cost of \$1B/150 MW_e = \$6.67/W_e. For comparison, natural gas power plants have an overnight cost \$1/W_e, solar photovoltaic \$1.7/W_e, and wind

[28] Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program, Bechtel National, Inc. Report No. 26029-000-30R-G01G-00001 Feb. 2017 woodruffscientific.com/pdf/ARPAE_Costing_Report_2017.pdf (accessed Oct. 21, 2018).

$1.5/$W_e$.[29] The last fission construction project in the US, the Vogtle Electric Generating Plant in Georgia, is in jeopardy due to cost overruns to > $25B, or $10/$W_e$.[30]

Intermittent operation in the context of renewables would hurt the economics of the notional plant. Capital cost-dominated energy sources such as fusion are more sensitive to intermittent operations than are fuel cost-dominated energy sources such as natural gas. These crude estimates demonstrate the challenging economics posed by the combination of natural gas and renewables: reactors are expensive and existing alternatives are cheap.

Response of commercial fusion enterprises: The proponents of the commercial fusion efforts are, of course, aware of these economic challenges. To mitigate, they seek to maximize the efficiency with which fusion energy is either converted to salable electricity or recycled to power the next shot. Enhancements in these efficiencies would increase the ratio of electrical output to fusion yield, decreasing overall capital costs.

In a D-T fusion reaction, 20% of the energy is released in alpha particles, and 80% in neutrons. The Helion device seeks to capture the energy from alpha particles in a direct-to-electrical conversion process, bypassing the inefficiencies of a thermal cycle for this portion of the energy. The Helion system provides the bulk of the plasma compression through a ramped magnetic field. They seek to recapture the magnetic energy in each shot via an inductive loop, further decreasing the quantity of electrical energy that must be recycled to recharge the capacitors for the next shot.

In the General Fusion device, the compression is driven by a collapsing molten Pb liner, rotated at high speed to form a central cavity. The design seeks to conserve the translational and rotational kinetic energy in the Pb from shot to shot, minimizing the amount of energy that must flow through a lossy thermal-electrical-mechanical loop to pump the molten Pb. Furthermore, the gas pistons that compress the molten Pb are pressurized via direct gas heating with the hot Pb efflux, again avoiding a lossy thermal-electrical-mechanical loop. These innovations seek to minimize the portion of electrical power which must be recirculated to operate the reactor.

These examples illustrate that economic viability will require innovations in the power harvesting and cycling aspects of the plant, not just the fusion core. Whether the engineering innovations will be sufficient to reach economic break-even (assuming the central reaction can be made to work at all) remains to be seen. Finally, there are niche applications in which the advantages of avoiding a hydrocarbon fuel supply chain might justify generation at much more than 5¢/kWh.

Non-U.S. grid: The economics of electric power production can be substantially different in other countries with different government policies; and where access to natural gas and renewables may be limited. For instance, the Chinese government reports that fission plants are being built for ~$2.4/$W_e$ in

[29] U.S. EIA, "Cost and Performance Characteristics of New Generating Technologies," *Annual Energy Outlook 2018*, Feb. 2018, Table 8.2. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

[30] Russell Gold, "Growing Opposition Threatens Completion of Last U.S. Nuclear Plant," Wall Street Journal, 20 Sept. 2018, https://www.wsj.com/articles/growing-opposition-threatens-completion-of-last-u-s-nuclear-plant-1537447935

China, less than a quarter the cost in the U.S..[31] Where a technology is invented, where it is manufactured, and where it is deployed are manifestly three different questions. It is possible, perhaps even likely, that a fusion power plant will be demonstrated outside of the U.S., and that the largest fusion power deployment will also happen in some other country. In such a scenario, the U.S. might still benefit by manufacturing the technology; and by supporting transitions away from fossil fuels in other countries.

The meaning of 'cost': At present, the science and engineering of fusion in any density regime entail too many profound uncertainties to support credible cost estimates for hypothetical commercial reactors. The scope of this study refers explicitly to 'low-cost' fusion, so we briefly discuss that modifier.

A possible interpretation of 'low-cost' is 'drastically less expensive and more convenient than all alternatives,' akin to the romanticized view of limitless energy "too cheap to meter" that would transform society. Such a condition seems both unlikely to be met, and unnecessary for fusion technology to be worth an investment.

An alternative interpretation of 'low-cost' is 'plausibly within the broad cost range of alternatives,' subject to learning and economies of scale. This does not guarantee 'preferable' or 'competitive.' The simple estimates above suggest that fusion reactors might be considered theoretically 'low-cost' at the same time as being uncompetitive with other electric generation resources.

A third interpretation of 'low-cost' is 'substantially less expensive than MCF or ICF to reach scientific break-even in a device configuration which could plausibly be further engineered into a power plant'. This definition takes the desirability of developing a fusion energy technology as a given, justified by the existence of substantial ongoing investments in MCF. The question, then, is "Does MIF get us to the most proximate milestone more economically and perhaps faster than the alternatives—ICF or MCF?" This is the interpretation we use in this Report.

2.4 Why Now?

Linhart *et al.* first described the physics underlying MIF in the Western literature in 1962.[32] Lindemuth and Kirkpatrick[33] advanced theoretical arguments in 1983 that MIF could reach break-even under less stringent conditions than MCF or ICF. The theoretical arguments underpinning MIF have been developed over the past 35 years and are summarized in a monograph by Garanin and Reinovsky.[34] There has been a recent surge in interest in MIF research, including a Summer 2018 IAEA-sponsored workshop on Fusion Enterprise[35], interest from venture capitalists[36], and of course the ALPHA program. What new information or technologies drive this interest?

[31] World Nuclear Association, China Country Profile (updated Aug. 2018): http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

[32] J. G. Linhart, H. Knoepfel, and C. Gourian. *Amplification of magnetic fields and heating of plasma by a collapsing metallic shell*. Euratom-CNEN, Frascati, Italy, 1962.

[33] I. R. Lindemuth and R. C. Kirkpatrick. "Parameter space for magnetized fuel targets in inertial confinement fusion." *Nuclear Fusion* **23**, 263 (1983).

[34] S. F. Garanin and R. E. Reinovsky. Physical Processes in the MAGO/MFT Systems. No. LA-UR-13-29094. Los Alamos National Lab.(LANL), Los Alamos, NM (2015).

[35] https://nucleus.iaea.org/sites/fusionportal/Pages/Enterprises/2018/General-Info.aspx

[36] http://issues.org/32-2/whats-the-big-idea/

Scientific breakthrough: On the scientific front, in 2014 the MagLIF project demonstrated fusion-relevant conditions, including a temperature of 3 keV and strong magnetic confinement.[37] These 'proof-of-concept' results catalyzed public and private interest in the MIF approach.

Technological advances: We identified three primary technology drivers of recent progress:

1) **Computation**. Many MIF concepts involve heterogeneous, dynamically varying magnetic fields, large gradients in density, temperature, and pressure, and heterogeneous boundaries between plasma and liner. Recent advances in computational power promise to enable simulations to understand and optimize these complex experiments.
2) **Power electronics.** MIF experiments require delivery of high-energy pulsed power over ns to ms timescales. These requirements demand high-energy-density capacitor and solid-state, high-current, high-voltage switching technologies. Recent advances in Linear Transformer Driver (LTD) technology have decreased the cost and improved the performance of stored-power electrical systems.[38] A single LTD 'brick' can deliver ~1 MA at ~100 kV over ~100 ns, corresponding to a peak power of ~10^{11} W and a delivered energy of 10^4 J.
3) **High-speed servo controls.** Several MIF concepts involve precisely timed launching of liner material from multiple directions—either liquid Pb liners or high-Z plasma jets—while others require precise relative timing of multiple current pulses. The ability to control precisely the strength and timing of high-energy sources is critical to maintaining the symmetry needed for high-compression implosions. Advances in 3D printing and high-speed, high-power controls facilitate implementation of these designs.

While the latter two technological advances might seem minor, the briefers made clear that all three capabilities are essential to current progress. We note that similar factors were identified in a 1996 joint report between the US and Russian MTF/MAGO teams, who wrote, "it is only in light of recent advancements in plasma formation techniques, implosion-system drivers, plasma diagnostics, and large-scale numerical simulation capabilities that the prospects for fusion ignition using this approach can be evaluated."[39]

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[37] M. R. Gomez et al. "Experimental demonstration of fusion-relevant conditions in magnetized liner inertial fusion." *Physical review letters* **113**, 155003 (2014).

[38] A. A. Kim, et al., "Development and tests of fast 1-MA linear transformer driver stages." *Physical Review Special Topics - Accelerators and Beams* **12**, 050402 (2009).

[39] I. R. Lindemuth, et al., "Magnetic-Compression/Magnetized-Target Fusion (MAGO/MTF): A marriage of inertial and magnetic confinement." No. LA-UR-96-3939; CONF-961005-14. Los Alamos National Lab., (1996).

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3 PHYSICS BACKGROUND

The energy contained in atomic nuclei can be tapped either by splitting a heavy nucleus into smaller ones (fission) or combining two small nuclei into a larger one (fusion). Fission (aka nuclear power) is a well-developed energy technology supplying 11% of the world's electricity[40], as well as propulsion for submarines and naval surface ships. Fusion, although common in the cosmos (it powers the stars), has so far found meaningful terrestrial application only in nuclear weapons. Achieving sustained and controlled fusion reactions would open the door to a new source of energy with intriguing advantages relative to existing sources.

3.1 Cross Sections

If two nuclei are to fuse, they must be brought to a separation r ~ several femtometers (1 fm = 10^{-15} meter), the characteristic size of light nuclei. The energy required to do that (the Coulomb barrier, U) is given by

$$U = \frac{Z_1 Z_2 e^2}{r} = 450\ \mathrm{keV}\ Z_1 Z_2 \left(\frac{r}{3\ \mathrm{fm}}\right)^{-1}$$

where $Z_{1,2}$ are the atomic numbers of the fusion nuclei. While the coulomb barrier is easily surmounted by an accelerator beam, energy applications involve thermonuclear fusion, where the nuclei collide due to their thermal motion in a hot plasma. Here the energies are necessarily much lower (a temperature of 1.2×10^7 K is only 1 keV), so that if the nuclei are to fuse, they must tunnel quantum mechanically thorough the Coulomb barrier (Fig. 5). These considerations imply that lighter nuclei (a more quantal system that tunnels more readily), smaller atomic numbers (lower coulomb barrier), and higher temperatures (more energetic collisions) will optimize the rate of thermonuclear fusion.

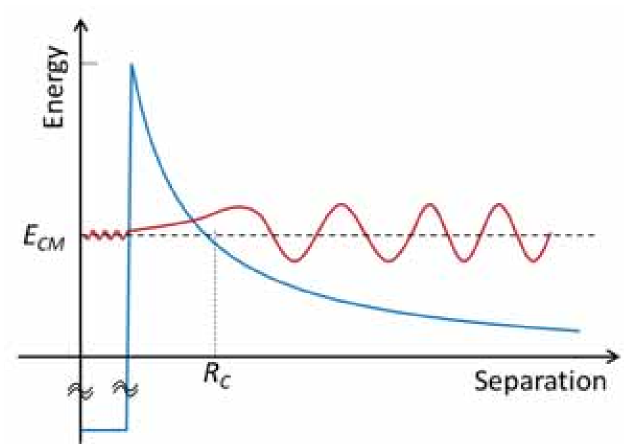


Figure 5. When nuclei collide and reach the classical turning point (R_C), there is a finite probability that the relative motion will tunnel through the Coulomb barrier and fuse.

[40] http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

Table 2. Energetics of low-Z reactions considered for fusion energy in MeV.

D + D	$\xrightarrow{50\%}$	T(1.011) + p(3.022)
D + D	$\xrightarrow{50\%}$	^{3}He(0.820) + n(2.449)
p + T	$\longrightarrow$	^{3}He + n − 0.764
D + T	$\longrightarrow$	^{4}He (3.561) + n(14.029)
T + T	$\longrightarrow$	^{4}He + 2n + 11.332
D + ^{3}He	$\longrightarrow$	^{4}He(3.712) + p(14.641)
T + ^{3}He	$\xrightarrow{59\%}$	^{4}He + n + p + 12.096
T + ^{3}He	$\xrightarrow{41\%}$	^{4}He(4.800) + D(9.520)
^{3}He + ^{3}He	$\longrightarrow$	^{4}He + 2p + 12.860

There are several possibilities for reactions among the isotopes of hydrogen and helium.[41] In Table 2, *p* and *n* are proton and neutron, respectively, D = ^{2}H (deuteron), and T = ^{3}H (triton). The numbers represent energy in MeV. The highlighted D + T reaction is favored in energy production schemes due to its large cross section (see below). There are other, minor reaction branches among these reactants, for example D + D → ^{4}He + ϒ (24 MeV), which proceeds at a rate some 10^7 times smaller than the branches shown. The reaction p + p → D + e$^+$ + ν_e, which is the dominant process in the Sun, has far too low a rate to be practical on Earth.

The DT reaction has several drawbacks. One is that 80% of the energy produced is carried by a 14.4 MeV neutron, which cannot be confined by a magnetic field, is highly penetrating (a 5 cm range in steel), and induces long-lived radioactivity as well as embrittlement in surrounding materials (by comparison, fission neutrons have energies around 2 MeV). Replacement of reactor walls will increase operating costs, cause down-time, and require handling low-level radioactive waste. A second drawback of the DT reaction is that tritium is radioactive, undergoing a beta decay to ^{3}He with a half-life of 12.3 years. As a result, the tritium fuel is not found in nature (unlike deuterium, which is 0.016% of natural hydrogen), but must be continuously produced ("bred") during reactor operation, usually by the ^{6}Li + n → ^{4}He + T reaction.

The multiple problems engendered by neutrons have led to consideration of aneutronic reactions such as ^{3}He + ^{3}He → ^{4}He + 2p + 12.86 MeV, and ^{11}B + p → 3 ^{4}He + 8.7 MeV. While the first suffers from both a low reaction rate (only 10^{-3} that of DT at a temperature of 100 keV) and a relative rarity of ^{3}He in nature (only 0.000137% of terrestrial Helium), some have considered ^{11}B + p a promising candidate (^{11}B is 80.1% of natural Boron), though the kinetics of this reaction are less favorable than the alternatives (see below).

Nuclear reaction rates are characterized by the cross section, σ, which expresses the probability of reaction in terms of an equivalent target area presented to the approaching particle. The cross section

[41] http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html

depends upon the speed of the collision (e.g., collisions at a higher energy will more easily tunnel through the Coulomb barrier); it is conventionally measured in units of barns (1 barn = 10^{-24} cm^2). Cross sections for reactions at thermonuclear energies are dominated by the quantum penetration of the Coulomb barrier, and so have the form

$$\sigma = \frac{S(E)}{E} e^{-R/E^{1/2}}$$

where E is the center-of-mass energy of the collision, $S(E)$ is a nuclear structure factor which in most cases varies slowly with energy (for a non-resonant reaction), and

$$R = Z_1 Z_2 \pi e^2 \sqrt{\frac{2m}{\hbar^2}} = 31.39\ \mathrm{keV}^{1/2}\ Z_1 Z_2 \left(\frac{m}{1\ \mathrm{AMU}}\right)^{1/2},$$

where $m = m_1 m_2/(m_1 + m_2)$ is the reduced mass of the collision. R characterizes the strength of the Coulomb barrier in the reaction.

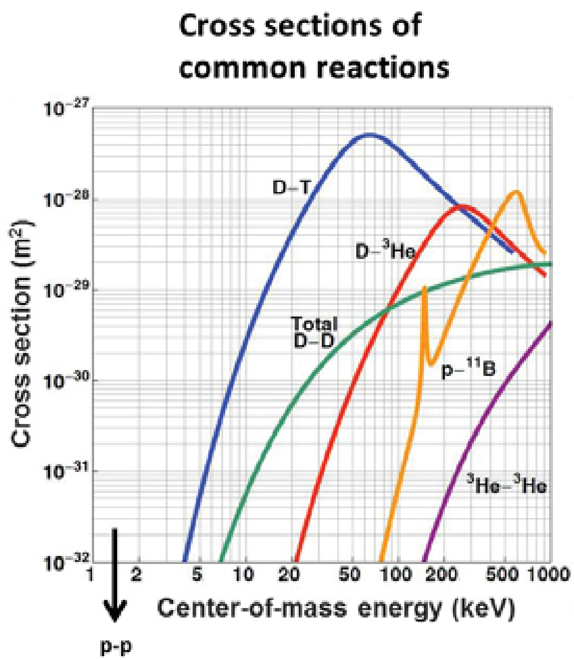
Figure 6 gives energy-dependent cross sections for reactions of interest. Table 3 shows approximate values of S and R for some common reactions, neglecting the energy dependence of $S(E)$.[42] In some reactions, such $p^{11}B$, sharp resonances in $S(E)$ contribute substantially to the cross section. Energy-dependent interpolation formulas for $S(E)$ for common reactions are in Ref. 43. DT has the largest cross section at thermonuclear energies both because of the low atomic numbers involved and because of a resonance in the compound nucleus ^{5}He.

Table 3: Cross section parameters for some fusion reactions

Reaction	*S* (barns-keV)	*R* ($\mathrm{keV}^{1/2}$)
D–D_p	52.6	31.39
D–D_n	52.6	31.39
D–T	9821	34.37
T–T	175	38.41
D–^{3}He	5666	68.74
T–^{3}He	2422	76.82
^{3}He–^{3}He	5500	153.7

[42] E. G. Adelberger, et al. "Solar fusion cross sections." *Reviews of Modern Physics* **70**, 1265 (1998).

[43] H.-S. Bosch and G. M. Hale. "Improved formulas for fusion cross-sections and thermal reactivities." *Nuclear Fusion* **32**, 611 (1992)



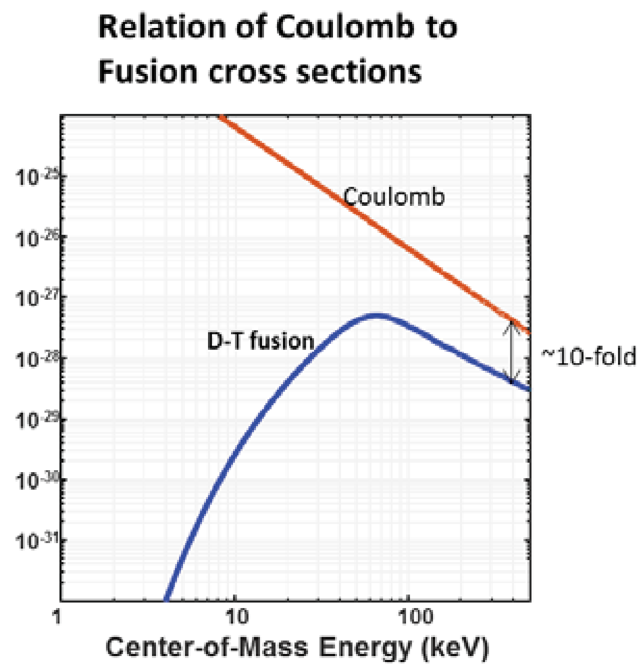


Figure 6. Fusion cross sections. A) Cross sections of common fusion reactions as a function of center-of-mass kinetic energy. The p-p reaction, which dominates in the Sun, has too low a cross section to be useful on Earth, due to the participation of the Weak interaction. B) Comparison of Coulomb and fusion cross sections for the D-T reaction. At all energies, Coulomb scattering is more likely than fusion. D-T data from [Bosch, H-S., and G. M. Hale. "Improved formulas for fusion cross-sections and thermal reactivities." Nuclear fusion 32.4 (1992): 611.]. The parameter ln Λ was set to 10.

Fusion reactions compete with non-productive Coulomb scattering, which can cause loss of particles and energy from the plasma. The Coulomb scattering cross-section decreases as kinetic energy increases because the classical Coulomb turning radius scales as $1/E$. Integrating over the differential cross-section yields an effective Coulomb cross-section:

$$\sigma_C = \frac{\pi e^4 Z_a^2 Z_b^2}{E_{cm}^2} \ln \Lambda$$

where the parameter $\Lambda = 12\pi n \lambda_D^3$, n is the particle density and λ_D is the Debye shielding length. Λ accounts for shielding of long-range electrostatic forces in the plasma. The parameter $\ln \Lambda$ varies by less than a factor of 3 for plasmas of interest in fusion research[44] (Table 4).

The ratio of Coulomb scattering to fusion events is given by the ratio of their cross-sections, each plotted in Fig. 6. This ratio is an important dimensionless parameter of a fusion system. It is a function of temperature, but only a weak function of density: both Coulomb scattering and fusion rates are proportional to n^2 leading to a cancellation in their ratio, but the Coulomb logarithm introduces an additional weak n dependence into $\sigma_{C>}$

[44] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion* (1984), Ch. 5.6, p. 169.

Table 4. Coulomb shielding parameters for some fusion-relevant plasmas.

KT_e (eV)	n (m^{-3})	ln Λ	
0.2	10^{15}	9.1	(Q-machine)
2	10^{17}	10.2	(lab plasma)
100	10^{19}	13.7	(typical torus)
10^4	10^{21}	16.0	(fusion reactor)
10^3	10^{27}	6.8	(laser plasma)

3.2 Reaction Rates

For a DT reaction, the rate (fusions per unit volume per second) is $\Gamma = n_D n_T \langle\sigma v\rangle$, where n is the number density of reactants and <σv> is the velocity-weighted average of the cross section over the Maxwellian distribution of (relative) velocities. Thus, for a plasma at temperature T

$$\langle\sigma v\rangle \sim \int_0^\infty dE\, S(E) e^{-E/T}\, e^{-R/E^{1/2}}$$

where the integral is over E, the relative energy of the collision. If one neglects the energy dependence of $S(E)$, then the integrand peaks at $E^* \approx \left(\frac{RT}{2}\right)^{2/3}$ or $\frac{E^*}{T} \approx \left(\frac{R^2}{4T}\right)^{1/3}$. For the DT reaction, R = 34.37 keV$^{1/2}$, so at T = 10 keV, $E^*/T \approx 3.1$, implying that most reactions occur in the extreme tail of the Maxwellian distribution (*i.e.*, only the very fastest particles participate). Inclusion of $S(E)$ in the integrand shifts this result to $E^*/T = 3.5$. Representative reaction rates are shown in Fig. 7.

3.3 Thermodynamics

For the DT reaction, the energy released is ΔU = 17.6 MeV per reaction. This energy is equivalent to 3.4×10^8 MJ/kg of DT fuel. For comparison, burning of methane releases 55 MJ/kg fuel. The power density (power per unit volume) of a fusion reaction is $P = \mathrm{n_D n_T}\, \langle\sigma v\rangle\, \Delta U$. To achieve scientific break-even, the power released must exceed the power supplied to assemble the fuel. The latter can be estimated by U_{int}/τ_E, where U_{int} is the internal thermal energy in the plasma, and τ_E is the energy dissipation time. The internal energy is well described by a simple ideal gas model, with $\frac{3}{2}T$ of energy per particle (where T is measured in energy units). In a neutral plasma $n_{electron} = n_{ion}$, and if one assumes all species have the same temperature, then for the DT reaction, $U_{int} = 3\, T\, n_{ion}$.

Assuming a 1:1 mixture of D and T (so $n_D = n_T = \frac{1}{2} n_{ion}$), then the break-even condition becomes:

$$n\tau_E \geq \frac{12}{\Delta U} \frac{T}{\langle\sigma v\rangle}$$

In MCF systems where the maximum pressure is relatively constant (set by the maximum magnetic field), then it is customary to multiply both sides of the above expression by T, yielding:

$$nT\tau_E \geq \frac{12}{\Delta U} \frac{T^2}{\langle\sigma v\rangle}$$

By the ideal gas law, the quantity $n\,T$ is the pressure. The quantity $\frac{T^2}{\langle\sigma v\rangle}$ has a minimum around $T = 14$ keV, and substituting this value, leads to the Lawson criterion, $n\tau_E T \geq 3\ \times 10^{21}\ \mathrm{keV\ s/m^3}$. Fig. 7 shows that this expression is approximate, valid for DT only at T = 14 keV. Higher or lower temperatures require a higher value for the triple product.

At thermonuclear temperatures ($T < 100$ keV), DT has the largest reaction rate by two orders of magnitude and hence is the favored candidate for most approaches to fusion energy. The $p^{11}B$ reaction has been considered as an aneutronic alternative to DT. Despite the large charge product ($Z = 5$ for boron), its rate of energy production per ion ($\Delta U \times \langle\sigma v\rangle$) is within an order of magnitude of DT at temperatures above 150 keV (Fig. 7). A resonance in the compound ^{12}C system helps here, although the high temperatures are much more challenging than those required for DT. The presence of 5 electrons per B atom doubles the heat capacity of the $p^{11}B$ plasma relative to DT, assuming electrons and ions are at the same temperature. Thus twice as much energy must be delivered to $p^{11}B$ relative to DT to reach the same temperature.

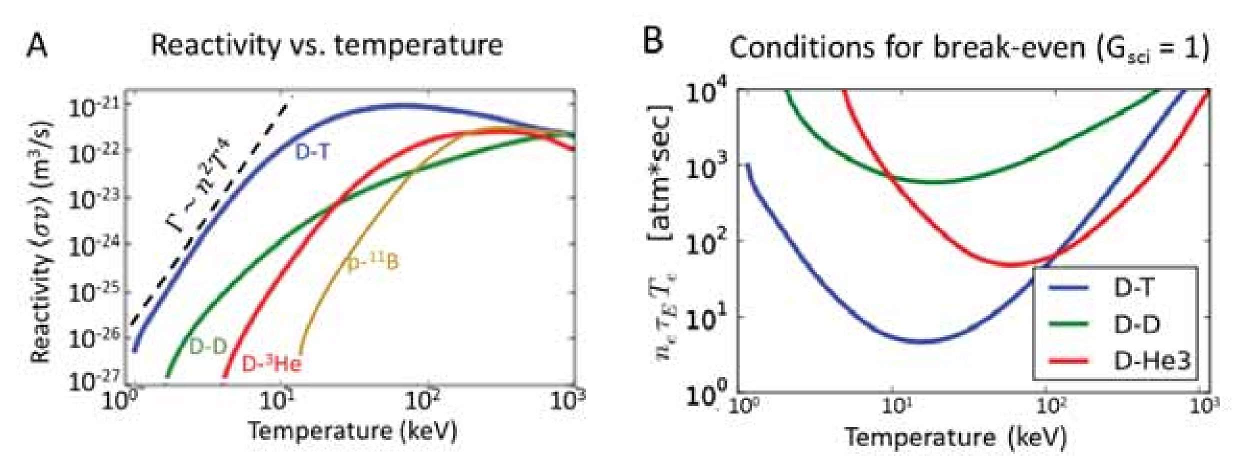


Figure 7. Thermodynamics of fusion reactions. A) Reactivity (reaction rate per particle) of the commonly studied fusion reactions. At temperatures < 100 keV, the DT reaction is most favorable, but at temperatures > 100 keV the $p^{11}B$ reaction becomes comparable. B) Triple product to achieve scientific break-even as a function of temperature. For the DT reaction, the optimal temperature is 14 keV.

3.4 Dissipation

Minimizing energy loss to the ambient environment is the primary challenge in every controlled fusion experiment. Energy is lost through photons, neutrons, and charged particles (electrons and ions). Neutrons escape freely and charged particle loss is described by the confinement time (which is different for the reactants than for the energetic charged products of the reactions).

Loss through photons is primarily via Bremsstrahlung radiation produced by electron-ion collisions. The radiative power dissipation is:

$$P_B \sim T_e^{1/2}\, n_e \sum_{ions} n_i Z_i^2 = \frac{Z_i^2 n_i n_e}{[7.69\ \times 10^{18} m^{-3}]^2} T_e[eV]^{\frac{1}{2}}$$

Figure 7A shows that for temperatures < 10 keV, the DT reactivity grows approximately as T^4, whereas the Bremsstrahlung power only grows as $T^{1/2}$. Both quantities scale as n^2, so their ratio is insensitive to density. For low-Z plasmas (e.g. DT), Bremsstrahlung radiation becomes insignificant relative to fusion power at temperatures above 4 keV. However, the Z^2 dependence imposes severe requirements on plasma purity. For instance, several MIF concepts contemplate using a Pb (Z = 82) liner to compress the plasma. Pb impurities at a concentration of ~10^{-4} relative to the fuel will approximately double the Bremsstrahlung rate.

While most analyses of MIF concepts have focused on minimizing transport of fuel nuclei to the reactor walls, **we note that transport of high-Z liner atoms into the fuel is a potentially serious problem that has received inadequate attention.**

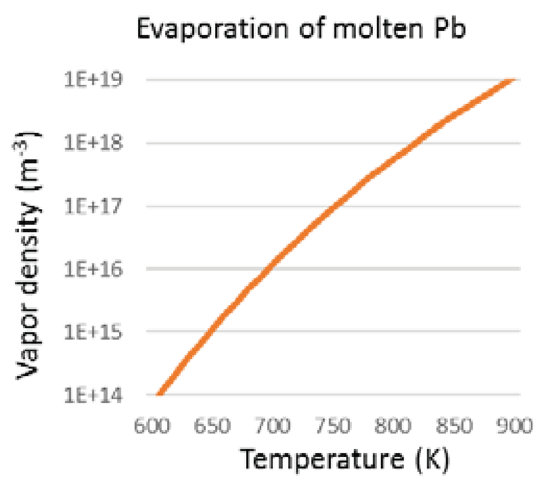


Figure 8. Equilibrium vapor pressure of lead as a function of temperature.

For solid and liquid liners, the problem of liner-fuel mix can be divided into two parts: 1) ejection of atoms from the liner surface; and 2) transport of these ions through the magnetized fuel. Fig. 8 shows the equilibrium density of Pb atoms in the vapor phase as a function of the surface temperature of molten Pb (melting temperature 601 K). This vapor pressure places a lower bound on the Pb density in the vapor phase during a MIF experiment with a Pb liner. During fuel compression, the Pb surface may be heated by plasma-wall collisions and by Joule heating from induced electric currents; and Pb atoms may be sputtered off the surface by high-energy neutrons and ions escaping from the plasma. Characterization of these effects will require an experimental program to study liner-plasma interactions. The results of these experiments should be the joint distribution of velocities and ionization states of atoms exiting the liner surface when in contact with the plasma under realistic conditions.

Liner-atom transport is also a complex process. Initially, neutral liner atoms will be able to penetrate the plasma without deflection by magnetic fields. As the evaporated or sputtered liner atoms heat, they will increase in both velocity and ionization state, while also affecting plasma parameters via Bremsstrahlung cooling. An improved understanding of this transport will be critical for mitigating technical risk in Pb liner-based approaches; and perhaps in other approaches with high-Z liners as well. This understanding will likely require a combination of experimental and computational work.

In addition to Bremsstrahlung radiative losses, high-Z impurities have another route to cool plasmas in pulsed systems: initially neutral liner atoms will absorb energy from the plasma as they heat and ionize. The n^{th} electron to be ionized from a liner atom will absorb $I_E^n + \frac{3}{2}k_B T$ of energy from the plasma, where I_E^n is the n^{th} ionization energy and $\frac{3}{2}k_B T$ reflects the translational kinetic energy after ionization.

4 MIF PHYSICS

A magnetic field can drive four distinct processes in a plasma

- Suppress transport of particles and energy across field lines;
- Confine and compresses the plasma: increase pressure and keep particles off reactor walls;
- Enhance α deposition to facilitate self-heating and sustained burn;
- Suppress some instabilities.

To achieve each of these benefits of a magnetic field imposes different design constraints. MIF devices can, in principle, benefit from all four mechanisms. In some MIF concepts the bulk of the mechanical compression comes from a collapsing liner, rather than from a magnetic field.

4.1 Size Scaling: Why ITER is Big and NIF Targets are Small

In any fusion scheme, one wishes to maximize the number of collisions that a particle undergoes before it exits the plasma, to maximize the likelihood of fusion. This simple principle leads to very different implications in MCF vs. ICF.

The low density (limited by the confining magnetic stress) and comparatively large gyroradii of MCF plasma requires large dimensions to minimize particle loss. The rate of loss is a function of the dimensionless parameter R/r_g, where $r_g \sim 1/B$ is the gyroradius. Thus an important figure of merit for tokamak designs is the parameter $B\ R$. The magnetic field in ITER is limited by the critical field of superconducting coils of the mid-1990s to 5.3 T. Improvements in high T_C superconducting magnets have increased the attainable magnetic field to ~12 T, enabling a corresponding down-scaling of Tokamak dimensions, and presumably costs. This scaling underlies the SPARC Tokamak effort.[45]

In ICF, the likelihood of an ion reacting is proportional to the column density, $\rho_f R_f$, where ρ_f is the final density and R_f is the final radius after compression. The density scales as $\rho_f = \rho_i R_i^3 / R_f^3$, so the column density scales as $\rho_i R_i^3 / R_f^2$. The upper limit on the initial density is set by material constraints: cryogenic solid hydrogen has a density of $n \sim 5 \times 10^{22}/\text{cm}^3$ at ambient pressure. The upper limit on the product $\rho_i R_i^3$ is set by the available impulsive energy: $3k_BT$ of energy must be delivered *per ion* to heat the fuel. Given these constraints, to maximize the column density one should minimize R_f, which is why ICF targets are small, compression is fast, and the convergence ratio (R_i/R_f) is as large as possible (nominally 30).

4.2 Elements of a MIF system

MIF lies between the limits of MCF and ICF. Most MIF research falls into the density range $n = 10^{18} - 10^{23}\ \text{cm}^{-3}$, a factor of 10^5. Not surprisingly, diverse approaches have been explored to cover such a broad range in final density. This diversity is a striking feature of current MIF research: whereas the MCF and ICF communities have, by financial necessity, each focused most effort on a single design, there was

[45] Greenwald, M., et al. "The High-Field Path to Practical Fusion Energy." Commonwealth Fusion Systems White Paper, http://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_184790.pdf (accessed 15 Oct. 2018)

not a clear front-runner among the 8 MIF projects briefed to JASON. This diversity reflects the early stage of the technology: most projects have not progressed to a level of development where the likely physical and engineering constraints apply. Here we review briefly the recent progress and current status of MIF efforts.

Generically, a MIF system requires a source of magnetized plasma and a means to compress the plasma. For the magnetic field to suppress heat loss, the field lines must either form closed loops entirely within the plasma, or the geometry should be cylindrical with an axial magnetic field with an aspect ratio >> 60, so that electron transport along field lines does not exceed cross-field ion transport. All DT MIF schemes aim for a temperature of T ~10 keV, so the scientific break-even constraints on the final plasma density and confinement time are inversely related: at $n = 10^{18}$ cm^{-3}, the confinement time must exceed $\tau_E > 300$ µs; at $n = 10^{23}$ cm^{-3}, the confinement time must exceed $\tau_E > 3$ ns.

Within these broad constraints, there are many options for plasma and liner (Figure 9). In the Marshall gun configuration, a radial current between a central and surrounding conductor produces a $\boldsymbol{j} \times \boldsymbol{B}$ force on the plasma (as in a rail gun), causing plasma to eject through a nozzle, carrying a circumferential magnetic field along with it. In the approaches of General Fusion and Hyperjet Fusion, the plasma detaches from the gun, forming a stable configuration with a toroidal magnetic field. In the FuZE apparatus, the plasma reconnects with a conducting wall perpendicular to the axis of symmetry, forming a cylindrical Z-pinch configuration (axial current, circumferential magnetic field).

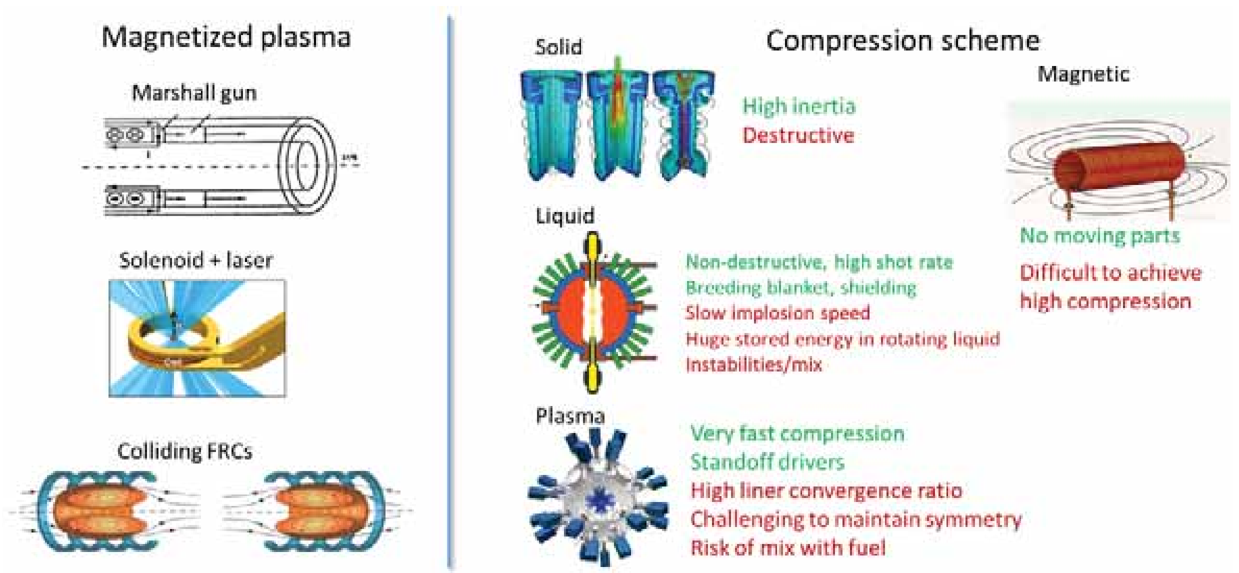


Figure 9. Ingredients of a MIF system. Many combinations of magnetized plasma and compression scheme are possible (though not all possibilities are practical). Only a subset of the plausible approaches has been tried.

An alternative approach is to use conventional coils to apply a magnetic field to a target prior to ionization, and then to use a laser pulse to ionize and pre-heat the plasma. This approach, used in the MagLIF and Omega experiments, works best in the high-density regime, where the fuel is sufficiently compact to be efficiently ionized by a focused laser pulse. The field lines are axially oriented and not closed in these geometries, so these require a very high aspect-ratio cylindrical compression.

The third approach to plasma formation in MIF is to produce a 'field-reversed configuration' (FRC). A cylindrical plasma is formed with an axial magnetic field. A rapid reversal of the applied magnetic field causes the field lines to close on themselves. Helion and Compact Fusion Systems have both proposed devices in which two FRCs are formed and then collided with each other to form an initially heated plasma.

The means of compression in MIF are also remarkably diverse, encompassing high-Z solid, liquid, and gas liners, and also purely electromagnetic drives. In the MagLIF system, a solid cylindrical can is caused to implode via an axial current pulse. These solid liners have the merit of having high inertia, and hence the ability to drive high compression; but the liners are destroyed in the process and it is hard to imagine how this configuration could solve the 'kopek problem'.

Compact Fusion Systems and General Fusion both propose to use collapsing liquid Pb liners. These liners are rotated quickly about the axis of symmetry to form a cylindrically symmetrical cavity, and then rapidly imploded by gas pistons to collapse on the plasma. As with the solid liners, the liquid liner has high inertia and so can drive strong compression; but in contrast to the solid liners, the liquid liner is regenerated with each cycle, offering the hope of a rapid repetition rate. The liquid Pb liner approach also addresses the issue of neutron damage to solid reactor walls. The Pb, if carrying ^{6}Li, also provides a substrate for breeding tritium, a necessary step in any self-sustaining DT fusion reactor.

The primary concerns with the liquid Pb liner are (a) whether the material can maintain adequate symmetry throughout the collapse, and (b) whether Pb ions will mix with, and quench, the plasma. The molten Pb fluid flow has been predicted to remain laminar and cylindrically symmetrical during the collapse,[46] stabilized by centrifugal forces provided that $\ddot{r} - \frac{v_\theta^2}{r} < 0$, where *r* is the inner radius of the liner and v_θ is the component of the velocity in the direction of rotation. Scaled experiments have supported this prediction.[47] But whether this stability will persist to fusion-relevant conditions remains to be seen. A sufficiently high gas pressure (e.g. driven by α heating) or magnetic pressure during stall and re-expansion could cause sufficient outward radial acceleration to violate the stability condition. Furthermore, the predictions of stability only apply about the rotation axis. In the orthogonal dimension the flow might not be stable, particularly near the poles in the case of a spherical collapse.

Liner-fuel mix could arise during a compression, as described above. Additionally, the intense energy released during a successful shot would be sufficient to vaporize the Pb surface (**Appendix D**), possibly terminating the reaction early either via liner-fuel mix or by disrupting the electric currents in the liner needed to maintain confinement. This vapor must be removed almost entirely from the chamber prior to the next shot, possibly limiting the repetition rate.

A secondary concern with the liquid Pb liner systems is to what extent the kinetic energy in the Pb can be recaptured after each shot to power the next shot. Commercial viability of these systems relies on efficient recapture, to minimize the amount of electrical energy that must be diverted to prepare the

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[46] D. L. Book, and P. J. Turchi. "Dynamics of rotationally stabilized implosions of compressible cylindrical liquid shells." *Physics of Fluids* **22**, 68-78 (1979).

[47] P. J. Turchi, *et al.,* "Rotational stabilization of an imploding liquid cylinder." *Physical Review Letters* **36**, 1546 (1976).

next shot. JASON is not aware of an analysis of the post-shot liner dynamics. There are concerns both at the inner surface (will the surface remain Rayleigh-Taylor stable?) and at the outer surface (how will the gas pistons be re-charged without disrupting the rotational flow of the liner?).

Gaseous (plasma) liners have also been considered in the Hyperjet Fusion and MIFTI systems. Hyperjet proposes to use plasma guns to drive a high speed (> 50 km/s) and approximately spherically symmetric collapse of a Xe plasma around a magnetized DT plasma target. MIFTI proposes to drive a Z-pinch current through a cylindrical high-Z noble gas liner, causing collapse on a cylindrical target ("staged Z-pinch"). The liner initially heats the target through shock heating, and then further heats the target adiabatically, in a geometry broadly similar to the MagLIF experiment. The merit of the gaseous approach is that there are no mechanical moving parts, giving the promise of high repetition rate and reliability. The first solid wall can be several meters from the reaction, decreasing neutron flux and associated damage.

The primary concerns with this approach are (a) whether the symmetry of the implosion can be maintained, (b) whether the high-Z liner will mix with the fuel, (c) the efficiency with which the liner transfers its kinetic energy to the fuel (since none of the liner kinetic energy is recaptured), and (d) how residual liner atoms will be removed from the chamber to prepare for the next shot. Whereas gaseous Pb atoms will stick upon collision with the (comparatively) cold liquid Pb wall, inert Xe atoms can be removed from the chamber only by mechanical pumping. JASON recommends estimating the time to evacuate the chamber post-shot (given a sufficient efflux aperture), as this time limits the ultimate repetition rate. A recent analysis cast doubt on the viability of the staged Z-pinch approach.[48]

Finally, several approaches have contemplated purely electromagnetic compression. The FuZE system uses an axial current through the plasma to drive a compressive $\boldsymbol{j} \times \boldsymbol{B}$ force. This 'Z-pinch' geometry was long-considered unworkable due to the emergence of multiple instabilities in the plasma ('sausage' and 'kink' instabilities). However, the FuZE team showed that these instabilities were suppressed in the presence of a radial shear in the axial flow velocity. By setting up a system in which the electric current simultaneously drove the Z-pinch and the shear flow, the FuZE team has argued that this approach will maintain stability up to fusion break-even conditions. The Helion system uses a large single-turn coil to produce a pulsed axial magnetic field that compresses the FRC-magnetized fuel. The purely electromagnetic approaches avoid issues of liner contamination and moving parts. The main challenge with these is whether they can simultaneously achieve sufficiently high compression while maintaining plasma stability. Table 5 gives the geometries and key physical parameters of some fusion approaches.

[48] I. R. Lindemuth, M. R. Weis, and W. L. Atchison. "The staged z-pinch as a potential high gain fusion energy source: An independent review, a negative conclusion." *Physics of Plasmas* **25**, 102707 (2018).

Table 5. Approaches to controlled fusion ranked by final density. ITER and NIF are included as the limiting cases. Temperature, density, and radius are reported at maximum compression. τ_E is the energy confinement time at maximum compression. Entries in **blue** represent data on integrated prototype systems. Other entries represent goal parameters.

Experiment	Plasma configuration	Compression	density (ions/cm^3)	Final B (T)	Final R (cm)	τ_E (s)
ITER	Tokamak	none	1E+14	5	240	3.6
Helion	Colliding FRCs	Pulsed B field	**8E+16**	**8**	**6**	**4E-05**
			3E+17	40	6	1E-03
[redacted]						
FuZE	Z-pinch	Shear-stabilized Z-pinch	**2E+17**	**8.5**	**0.3**	**5E-06**
			1E+20	50	<0.1	5E-06
Compact Fusion Systems	Colliding FRCs	Liquid Pb blanket	1.4E+18	130	3.4	Data not available
MIFTI	Z-pinch with axial magnetic field	Staged noble gas Z-pinch	3.5E+20	200	0.14	2E-09
Hyperjet Fusion LANL	Spheroidal	High-Z plasma jets	5E+21	300	0.5	1E-06
MagLIF on Z	Axial magnetic field and laser heating	Z-pinch in a metal can	**1E+23**	**14000**	**0.006**	**2.5E-09**
			4.5E+23	14000	0.008	2.5E-09
MagLIF on Omega	Axial magnetic field and laser heating	Laser direct drive	**2.75E+23**	**10000**	**0.001**	**3E-10**
NIF	Spherical	laser indirect drive	**2.5E+25**	**0**	**3.5E-03**	**1.5E-10**

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5 RECENT ADVANCES IN ALPHA PROJECTS AND ELSEWHERE

5.1 Progress along Key Metrics

Figure 10 summarizes recent progress in the MIF projects in parameter space (triple product vs. temperature) and Figure 11 shows the same data as a function of time, with future projections included.

Figure 10A gives the illusion that we are 'almost there': many fusion efforts show a steady march toward the break-even condition. Why have so many efforts gotten so close, but not reached break-even? The truth is that no efforts are close to break-even: the proximity is an artifact of the logarithmic axes. Fig. 10B shows the same data on a linear scale. The closest MIF effort, MagLIF, must either increase nTτ by a factor of 2, or increase temperature by a factor of 1.5 to reach scientific break-even. The next-closest effort, at the LLE/Omega system, must increase temperature by a factor of 3 and density by a factor of 2.5 to reach scientific break-even. No other MIF project is within two orders of magnitude of scientific break-even. To the extent that input energy scales with temperature, and that costs scale with input energy for a given technology, substantial financial investments would be required to upgrade the near break-even systems to achieve that goal.

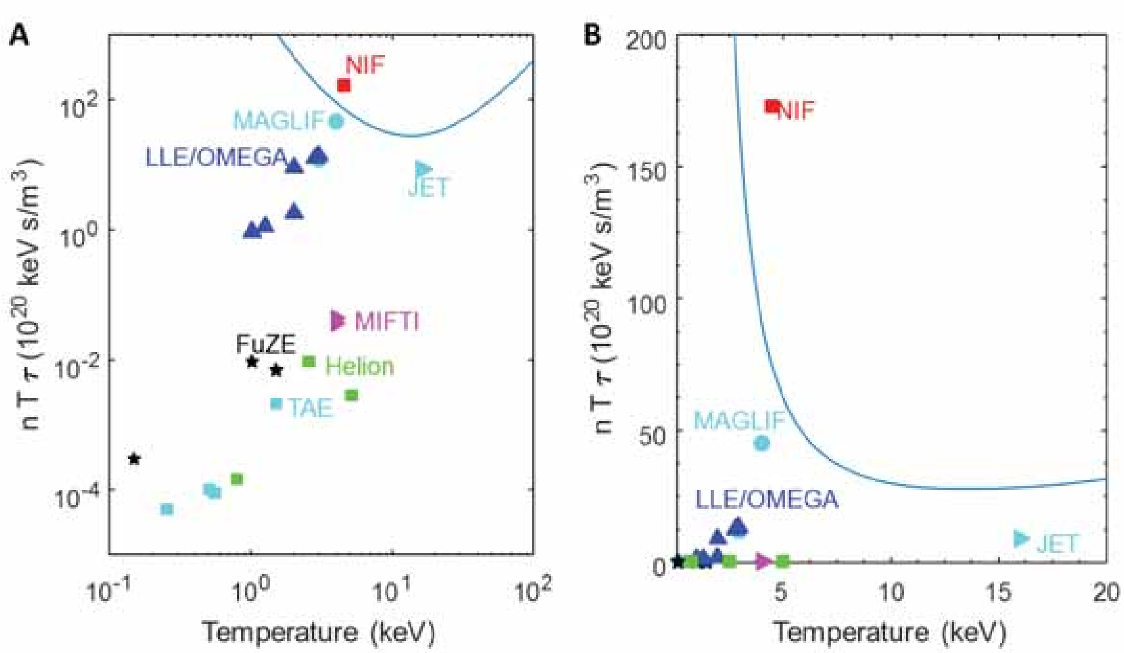

Figure 10. MIF efforts toward scientific break-even (blue curve). Tokamak programs (JET) and the NIF are included for comparison. A) Experimental results plotted on a log-log scale, as is customary. B) Same data plotted on a linear scale, highlighting the distance between most MIF programs and scientific break-even conditions.

5.2 Examples from Select Projects

Here we describe recent progress in two MIF projects to illustrate the challenges and opportunities.

MagLIF: One ALPHA-supported project, MagLIF at Sandia, differs from the others in that it is carried out exclusively at a National Laboratory, and so benefits from previous Federal investment in a large pulsed-power driver, the ZR machine (the Z-machine after a refurbishment of the pulsed power system in 2006/7). Fusion research began at Sandia in the 1970s and has been pursued on a sequence of several increasingly powerful pulsed-power machines, measured for example by peak current, now up to 22 MA on today's ZR. Several approaches to fusion have been pursued, including particle beams and Z-pinches, the latter through both indirect drive and, later, direct drive of a target containing fuel. Sandia researchers believe that break-even would be achievable on a new pulsed-power machine several times more powerful than ZR.

As the MIF effort closest to scientific break-even, the MagLIF project has a unique potential to inform the other MIF projects. Sandia should publish its open results on MagLIF for the benefit of the entire fusion community; JASON recommends that the backlog of unpublished results be published expeditiously. JASON notes that many studies on MagLIF could inform other MIF efforts, without requiring substantial upgrades to ZR. For instance, studies of cross-field transport in the MagLIF plasmas could inform other efforts that produce plasmas with comparable parameters (FuZE, MIFTI, HyperJet). MagLIF experiments with Pb liners could yield important information on Pb cross-field transport, which could inform the efforts that propose to use a collapsing liquid Pb wall (General Fusion, Compact Fusion Systems).

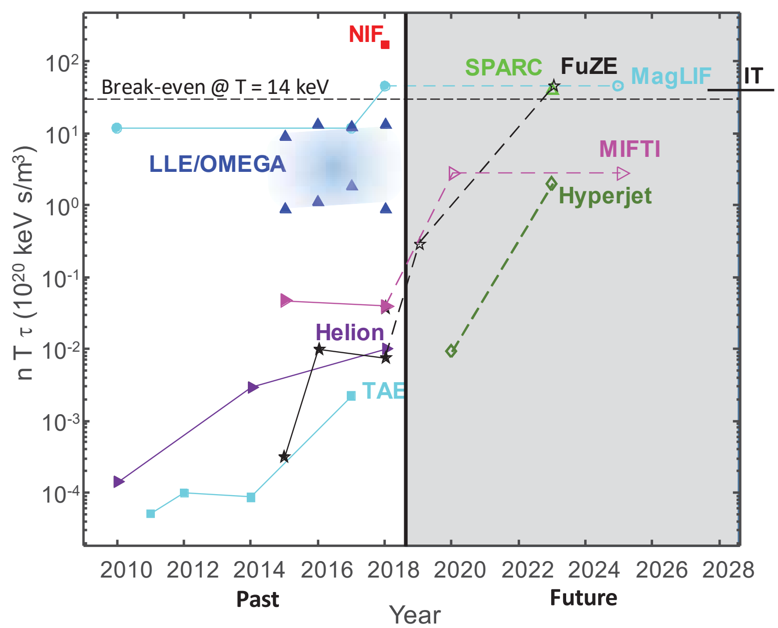

Figure 11. MIF progress vs. time toward scientific break-even. Filled symbols represent past results, empty symbols represent future projections. Tokamak programs (ITER, SPARC) and the NIF are included for comparison. The indicated break-even condition is specific to T = 14 keV. MagLIF did not achieve break-even despite crossing this threshold in triple product because MagLIF was too cold.

Sandia has developed an impressive suite of diagnostics on ZR, many of which might apply to other fusion projects, and sharing should be encouraged. As well, Sandia along with LLNL and LANL have great expertise in simulation codes, some of which has been shared with the wider community; such sharing should be further encouraged.

JASON recommends that proposals to increase the power at ZR and at the LLE not be justified solely on the basis of reaching scientific break-even. Reaching this condition, for its own sake, carries little value. JASON assesses that the solid liner MagLIF approach is unlikely to be scalable to a low-cost, high repetition-rate system, as needed for a power plant. Thus the value in MagLIF is in the physics learned, and disseminated to the community. Upgrades in power at MagLIF should be justified by the new physics to be learned; and weighed against the physics that could be learned by exploring different geometries, liner materials, diagnostics, or other experimental parameters with the current power level.

Shear-stabilized Z-pinch (FuZE): The FuZE program is notable as a primarily academic effort that has achieved substantial progress in neutron production in recent years. While Z-pinch approaches to fusion have been considered since the 1950s[49], early efforts were limited by instabilities. The key insight underlying the FuZE program was that at a sufficiently high laminar shear rate, the peaks and troughs of emergent instabilities would be mixed together. If the mixing of peaks and troughs exceeds the instability growth rate, then the instabilities would be quenched.[50] This theoretical prediction has been borne out by experiments that have increased the triple product 30-fold in the last three years. One of the further merits of this system is that as a purely electromagnetic compression system, it is capable of running at ~50 shots/day, enabling rapid explorations of parameter space and providing a path to sufficient repetition rate to be used in a practical power generating capacity.

5.3 Classification by Dimensionless Parameters

We wish to identify important dimensionless parameters that characterize the local properties of a MIF plasma. There are two such parameters. The first is the ratio of the Coulomb mean-free-path (mfp) λ_i of the ions to the cyclotron radius r_g. The Coulomb MFP is:

$$\lambda_i = \frac{(4\pi\epsilon_0 T)^2}{\pi n e^4 Z^4 \ln\Lambda}$$

The ratio λ_i/r_g is called the 'collisionality', and is large in MCF and small in ICF. When the collisionality is large, the transport properties of the plasma are anisotropic, whereas when it is small, the transport is approximately isotropic.

The second important parameter is the ratio of the plasma pressure, $n_{tot}T$, (or equivalently the energy density in the kinetic energy of plasma particles) to the magnetic pressure, $B^2/2\mu_0$ in SI units (or equivalently the energy density in the magnetic field). The ratio

$$\beta = \frac{2\,\mu_0 n T}{B^2}$$

is small for MCF and large for ICF. For large β the role of the magnetic fields can be largely ignored in the hydrodynamics, while for small β seen in, e.g., tokamaks, they play a dominant role.

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[49] J. L. Tuck, Method and apparatus for producing neutrons and other radiations. U.S. Patent No. 3,037,921. 5 Jun. 1962.

[50] U. Shumlak, et al. "Increasing plasma parameters using sheared flow stabilization of a Z-pinch." Physics of Plasmas **24**, 055702 (2017).

In Table 6, we list a sampling of the current approaches to fusion, ranging from the low-density, magnetically confined regime (as in the ITER facility) to the high-density, inertially confined regime, indicated with the NIF experiment. In the pulsed approaches where the density and the magnetic field strength evolve as a power of the convergence ratio, we use the target endpoint quantities that are important for confinement and breakeven goals in these experiments. We note that the data combines experimental data (MagLIF, NIF) with projections of future results (all others).

For the estimates in the table, we take the ion and electron densities and temperatures to be equal to the plasma density $n_i = n_e = n$, and temperature $T_i = T_e = T$, respectively and set the latter to 10 keV. We also assume a hydrogen plasma (D-T mixture) and set the atomic charge to be $Z = 1$ and the Coulomb logarithm ln Λ to 12.

Table 6. Dimensionless parameters of fusion efforts. Parameters are approximate and are drawn from literature sources and communications with the project leads. Entries in **blue** represent data, other entries are projections. Parameter definitions: n_i: ions density at maximal compression. B: magnetic field (Tesla) at maximal compression. R: plasma radius (along smallest dimension if not spherical) at maximal compression. β: ratio of thermal to magnetic pressure. λ_i: ion mean-free path. $\omega_{c,i}$: angular cyclotron frequency of ions. ν_i: frequency of Coulomb scattering events for ions. r_i: cyclotron radius. The last column gives the ratio of gyrofrequency to collision frequency for ions.

Experiment	**density (ions/cm³)**	**Final B (T)**	**Final R (cm)**	**Final T (keV)**	**β**	**λ_i/R**	**r_i/R**	**$\omega_{c,i}/\nu_i$**
ITER	1E+14	5	240	8	0.013	3.4E03	1.7E-03	2.0E06
Helion	**8E+16**	**8**	**6**	**2**	0.95	**11**	**0.021**	**500**
	3E+17	40	6	10	0.95	71	9.5E-03	7.5E03
[redacted]								
FuZE	**2E+17**	**8.5**	**0.3**	**1**	**1**	**21**	**0.28**	**76**
	1E+20	N.D.	<0.1	10	N.D.	13	N.D.	N.D.
Compact Fusion Systems	1.4E+18	130	3.4	22	0.73	130	7.7E-03	1.7E04
MIFTI	3.5E+20	200	0.14	4.5	16	0.53	0.055	9.7
Hyperjet Fusion LANL	5E+21	300	0.5	10	224	0.051	0.015	3.4
MagLIF on Z	**1E+23**	**14000**	**0.006**	**2.5**	**0.5**	**0.013**	**0.014**	**0.98**
	4.5E+23	14000	0.008	10	9.3	0.036	0.020	1.75
MagLIF on Omega	**2.75E+23**	**10000**	**0.001**	**2.9**	**3.2**	**0.041**	**0.13**	**0.32**
NIF	**2.5E+25**	**0**	**3.50E-03**	**4.5**	**>> 1**	**3E-04**	**>> 1**	**<< 1**

In addition to the local parameters, there are several dimensionless parameters that capture aspects of the overall geometry. Geometry is critical in determining loss rates (surface-to-volume ratio) and also in governing onset of instabilities. The most fundamental parameter is *N*, the mean number of Coulomb collisions a particle undergoes before it either exits the plasma or the plasma cools by adiabatic expansion.

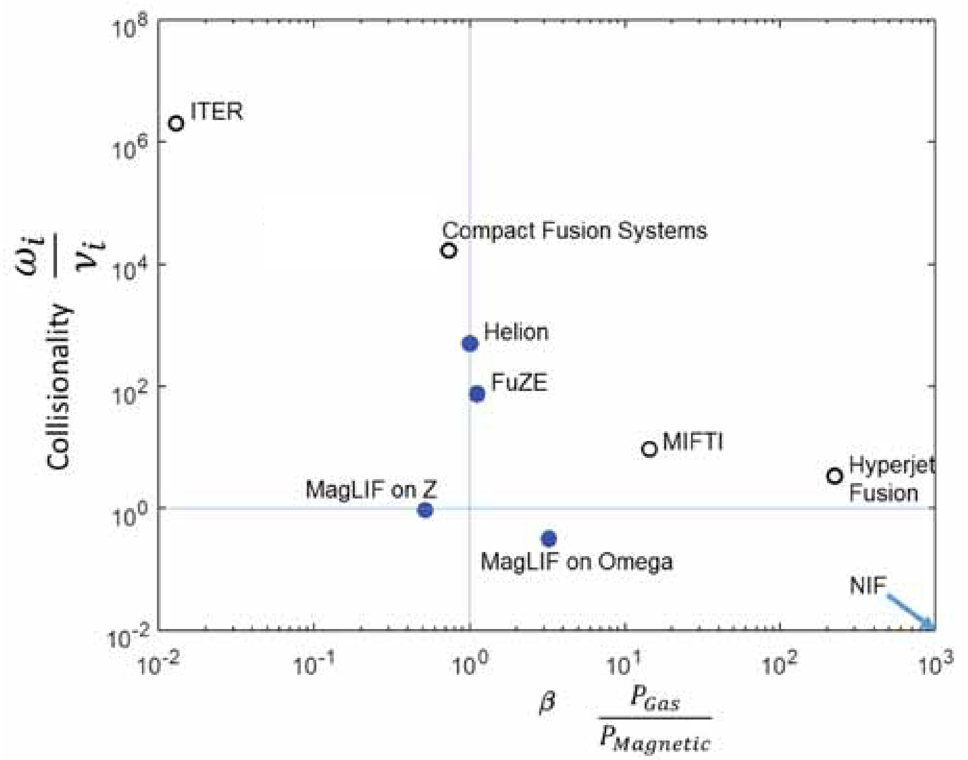

Figure 12. Fusion efforts arranged by dimensionless parameters. Empty circles represent projections, filled circles represent data. Parameters are approximate and are drawn from literature sources and communications with the project leads.

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6 FUNDAMENTAL TECHNOLOGY NEEDS TO ADVANCE SMALL-SCALE FUSION RESEARCH

6.1 Computational Modeling of Experiments in the MIF Regime

Why Computations? Computational modeling has been crucial for designing, interpreting, and scaling fusion experiments. High fidelity models can help with performing parameter scans for optimizing experimental setup as well as for scalability studies. When interpreting experimental results that incorporate numerous physical effects, computational modeling allows numerical investigations of specific concepts that can help isolate individual effects. Verifying computational models against experimental results can lead to a deeper understanding of the microphysics that contribute to fusion experiments.

Computational modeling is also used frequently for planning purposes. Models can lead to the development of advanced approaches for improved control. Predictive modeling improves extrapolations from regimes currently tested to different system parameters and help reduce risks. Finally, because numerical experiments are cheaper and faster than physical ones, they can help with the continued low-cost training of future scientists.

Reaping these benefits requires computational tools that can faithfully reproduce the outcomes of physical experiments. This is a worthwhile but challenging task, for the reasons discussed below.

Modeling approaches in different regimes. In the low-density tokamak regime, the mean-free-path is many times the system size R and hydrodynamic approaches are not applicable. Instead, codes that solve for motions of individual particles, such as particle-in-cell (PIC) and gyrokinetic codes are utilized.

In the opposite, inertial confinement, regime, the mean-free-path is much smaller than other characteristics lengths in the system (i.e., system size and the ion gyro radius) and the fluid approximation is appropriate. Here, hydrodynamic codes are widely used.

By definition, the magneto-inertial fusion (MIF) regime falls between these two extremes in both of these key parameters but the various approaches themselves span a significant range in density and β, as can be seen in Table 6. Because of that, the selection of the appropriate computational tools and their applications depend sensitively on the details (i.e., whether a particular setup is closer to magnetic or inertial confinement). In general, the global properties of the plasma generated in MIF experiments typically require magnetohydrodynamic (MHD) approaches to model. In this regime, the fluid approximation holds but the magnetic field has dynamical effects on the plasma.

Further considerations within the MHD regime are related to the dissipative effects in the plasma. Ideal MHD equations neglect any dissipative effects such as resistivity and viscosity, resulting in hyperbolic equations, which are more tractable computationally. However, there are numerous non-ideal effects such as (anisotropic) resistivity, viscosity, anisotropic thermal conduction, and separate ion and electron temperatures, some of which can be captured by the generalized Ohm's law and can be added as extra terms to the MHD equations.

As an example, anisotropies in the dissipation terms can be characterized by considering the ratios of the cyclotron frequencies to the Coulomb collision frequencies for the ions and the electrons. The cyclotron frequency for the ions can be expressed as

$$\omega_{c,i} = 9.6 \times 10^3 \left(\frac{B}{G}\right)\left(\frac{m_p}{m_i}\right) Z \,\mathrm{rad\, s^{-1}}$$

and is scaled by the relevant mass ratio for the electrons. The collision frequency ν_i is simply the ratio of the thermal speed to the mean-free-path. The last two columns of Table 6 show this ratio for the ions and electrons evaluated for the parameters of the various experiments. The setups for which these ratios are ≥ 1 need to account for anisotropic dissipation terms. When such terms are added, the mathematical character of the equations change to parabolic, significantly increasing the computational complexity.

In practice, the distinctions are not as clear cut and hybrid approaches are also employed to appropriately cover the landscape. For example, a fluid (MHD) approach might be sufficient to model the bulk of the plasma but small-scale plasma instabilities might require one to accurately capture particle distributions and resistivities (through, e.g., a PIC code) to account for heat transport. Furthermore, for many experimental setups, there are large gradients in density within the plasma cavity and large evolution of the parameters from the initial setup to the point of ignition that are not captured by the typical values shown in Table 6. In devices with solid or liquid liners, one must include dynamics across interfaces with dramatically different atomic numbers and weights. At the plasma-liner interface, there can be near-discontinuities in physical parameters and dynamical regimes, requiring very fine meshing. These factors often necessitate a combination of approaches to cover the entire range of physical conditions.

In addition to modeling the plasma, the transport of neutrons through the experimental cavity is needed to track yields and energy losses. While the radiation energy density is low compared to thermal and magnetic energies, some approaches also require an accounting for the transport of energy through radiation, such as when high-Z impurities mix into the plasma and enhance Bremsstrahlung radiation. Though radiation does not account for a significant portion of energy loss from an unmagnetized plasma, radiation may become a substantial source of wall heating in the presence of strong magnetic fields.

Dimensionality in models. Two geometries are employed in the codes to capture the geometry of the plasma: cylindrical and spherical. Even though the global symmetries would in principle allow the codes to be simplified to a 2D geometry, the instabilities and small-scale fluctuations that play important roles in the fusion problem necessitate working in 3D, making the computations expensive. During the implosion and ignition, the domain shrinks by the compression factor $C \equiv R_i/R_f$. Depending on the geometry, quantities of interest such as density and temperature scale as third or second powers of C. Handling these changes requires moving mesh/adaptive approaches.

Community needs. JASON surveyed the MIF community to determine computational bottlenecks and needs. Uniformly, the responses indicated that there are simulations the groups would find helpful to run, but cannot. The stated reasons behind this were:

1. Lack of software that can capture all the required physics (indicating the need for code development);

2. Lack of expertise to set up and run the appropriate simulations (indicating the need to cultivate and hire talent in this field);
3. Lack of computing resources, especially outside of national labs (indicating that ALPHA-like programs should consider providing awards on high-performance computing along with grants);

with #1 and #2 having a larger impact than #3. The inaccessibility of codes (e.g., because they are classified or proprietary) was mentioned by some respondents but was not a dominant concern; though it was not apparent whether all respondents knew about the capabilities of classified codes.

Other computationally intensive fields have adopted creative strategies advance the state of the art. The MIF community could draw inspiration from these approaches. Examples include:

- **Competitions**. Fusion physics is an exciting area with the possibility to recruit widespread talent in the development of advanced software. Contests have driven significant progress in software development in other fields. Examples include the **Critical Assessment of Protein Structure Prediction (CASP),**[51] and the **DARPA Grand Challenge** for self-driving cars.[52] These annual competitions have helped benchmark progress in the field, and serve a recruiting and training function as well. The competition meetings provide a platform for seeding collaborations and exchanging information. In the context of MIF research, one could select a challenging problem (e.g., a collapsing, inhomogeneous, magnetized plasma), and challenge teams to simulate an experimental result. Pairing software and hardware development, as in the DARPA Grand Challenge, could further advance the field.
- **Distributed Computing.** Many computationally intensive fields have developed distributed computing 'screensavers' which use idle computing power over the internet, e.g. in protein folding simulations (folding@home) and in the Search for Extraterrestrial Intelligence (SETI@home). More recently, the availability of computing power for rent on platforms such as Amazon Web Services gives access to nearly arbitrary computing power without requiring major capital investments. Efforts should be made to adapt MIF simulations to these platforms.

6.2 Instabilities and Loss Mechanisms

A common feature of all historical efforts at controlled fusion has been that instabilities made the problem harder than initially thought. Under conditions far from break-even, simple scaling rules governed the relation between energy inputs and final density, temperature, and confinement time. But as energy inputs grew, plasma parameters deviated below expectations. There is no reason to think that MIF experiments will be immune from these generic features of highly compressed plasmas.

Plasma instabilities can be divided roughly into two classes: fluid and kinetic. In a fluid instability the plasma can be described by macroscopic thermodynamic variables (electron and ion temperatures, densities and velocities of each species) that are continuous functions of space. The local distribution functions are equilibrium (Maxwellian). Hydrodynamic and magnetohydrodynamic instabilities (kink, sausage, Rayleigh-Taylor, Kelvin-Helmholtz, etc.) are examples of fluid instabilities. In a kinetic instability the local distribution function is non-equilibrium, and this local deviation from equilibrium provides the

[51] http://predictioncenter.org/

[52] http://archive.darpa.mil/grandchallenge/

free energy that drives the instability. Familiar examples are the "two stream" or "ion-acoustic" instabilities that occur when a beam of particles penetrates a plasma, or when there is a relative electron-ion drift.

While the complete zoology of plasma instabilities is too large to review, we note some generic features of instabilities that will apply to MIF experiments.

1) The characteristic rate of instability growth is typically much greater than any macroscopic rate (nuclear reaction or collisional energy loss) of the plasma. For magnetohydrodynamic instability it is an Alfven wave frequency, while for a kinetic instability it is a weighted geometric mean of the plasma and gyro frequencies. When the growth rate is negative, the mode of concern remains at small amplitude. When its growth rate turns positive, even if its suitably nondimensionalized growth rate is small, it grows and saturates rapidly. Saturation typically occurs at large enough amplitude to disrupt the plasma or to produce catastrophically rapid loss of plasma particles or energy. Experiments give little or no warning of instabilities until they occur. This feature of instabilities urges caution in simple scaling extrapolations.
2) Geometry matters. MIF experiments have a wide diversity of geometries, and there is no consensus on which are superior. The arguments for most MIF concepts motivate the geometry from simple scaling considerations, but those arguments might miss important instabilities, which often depend on plasma aspect ratio or topology.

The analysis of plasma parameters above focused solely on local variables (temperature, density, magnetic field strength), and global geometry. But instabilities in a fluid are often driven by gradients in physical parameters (*e.g.,* the onset of instability in Rayleigh-Benard convection, depends on a combination of material parameters, temperature gradient, and overall geometry). The possibly relevant gradients in MIF include gradients in:

- Temperature
- Density
- Flow velocity
- Magnetic field
- Electric field
- Composition

In the parameter space of MIF, the stability of plasmas under gradients in these quantities has been inadequately studied. While one often worries about gradients driving instabilities, they can have a stabilizing effect too. Magnetic shear has been used to stabilize tokamak plasmas.[53] Under some circumstances, shear flows can also suppress turbulence and transport, by mixing regions with oppositely directed motion before these motions can grow to substantial amplitude.[54] This principle has been used

[53] E. J. Strait, et al., “Enhanced confinement and stability in DIII-D discharges with reversed magnetic shear.” *Physical Review Letters* **75**, 4421 (1995).

[54] P. W. Terry, Suppression of turbulence and transport by sheared flow. *Reviews of Modern Physics* **72,** 109 (2000).

to good effect in stabilizing a Z-pinch geometry,[55][56] which had been long discarded due to susceptibility to instabilities.

Growth of asymmetries. Imperfections in the initial symmetry of a fusion target can seed the growth of instabilities, or can become amplified during compression and lead to energy loss even in the absence of a formal instability. In tokamaks, the boundary conditions are set by the tokamak walls and the magnetic coils. These are precisely engineered prior to plasma formation. In ICF experiments, the initial conditions (hohlraum geometry, capsule symmetry) are precisely engineered prior to each shot. Despite these efforts, slight asymmetries in ICF targets have been a major challenge at NIF.[57] In most MIF approaches, neither the boundary conditions nor initial conditions are well defined: a dynamically evolving magnetized plasma is compressed by a dynamically evolving collapsing liner. The challenges of establishing sufficient initial symmetry to attain a homogeneous compression merit further study.

Loss mechanisms. Simple scaling arguments may miss important energy and particle loss mechanisms that decrease the energy confinement times in MIF plasmas. In MCF tokamaks, energy loss is primarily through particle transport to the edges of the confining magnetic field. Since cooling is at the surface, there is a motivation to minimize the surface-to-volume ratio by making the plasma large. In ICF, the plasma cools by adiabatic expansion in the bulk, and the rate of expansion sets the energy confinement time. In the intermediate MIF regimes the plasma will cool both via surface evaporation and via bulk expansion. The combined influence of these two mechanisms requires further study.

Finally, the physics of plasma-liner interactions is an area of technical risk and interest for MIF research. In all MIF approaches with physical liners, the liner comes into direct contact with the plasma. In MIF, the compression is slower than in ICF, giving more time for liner to mix into the plasma, where it can quench the fusion reaction. In the research reviewed by JASON, liner mix was primarily treated as an empirical variable. Development of theoretical principles and experimental knowhow to minimize liner mix would be beneficial. Recent ICF results at NIF benefited from a thin carbon film deposited on the inside of the hohlraum.[58] We suggest studies of multi-layer liners where a low-Z material provides some standoff from a high-Z pusher.

A further concern with ultimate high repetition rate power systems will be removal of high-Z contaminants from preceding shots.

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[55] U. Shumlak, et al., Increasing plasma parameters using sheared flow stabilization of a Z-pinch. *Physics of Plasmas* **24,** 055702 (2017).

[56] Y. Zhang, et al., "Sustained neutron production from a sheared-flow stabilized Z-pinch." *arXiv:1806.05894* (2018).

[57] V. A. Thomas and R. J. Kares. "Drive asymmetry and the origin of turbulence in an ICF implosion." *Physical Review Letters* **109,** 075004 (2012).

[58] S. Le Pape, et al., "Fusion energy output greater than the kinetic energy of an imploding shell at the National Ignition Facility." *Physical Review Letters* **120,** 245003 (2018).

6.3 Diagnostics

Diagnostics play an essential role in all the alternative approaches JASON was briefed on. They include:

- **Measurements of currents and magnetic fields**; these are essential for any approach involving magnetized plasmas, and relatively straightforward.
- **Optical or UV imaging**. Straightforward (if opacity allows) and often helpful.
- **Point measurements of plasma densities and temperatures** at ~100 eV and above. Difficult to carry out, especially of density, but key to understanding the success of compression.
- **X-ray imaging** of plasmas at temperatures at ~100 eV and above. Difficult, but key to understanding instabilities. Time-dependent imaging is especially valuable if achievable.
- **X-ray spectroscopy**. Difficult but valuable.
- **Neutron output** is the “proof of the pudding” but difficult to measure well. A most important issue is whether the neutrons are produced by nuclear reactions in a thermal plasma (as is essential for break-even), or by in-flight reactions of beam nuclei or superthermal nuclei. To distinguish, neutron time-of-flight measurements over long distances are needed, with large-area detectors.

There is a need to develop highly sensitive diagnostic systems to monitor fusion reactor performance that operate with sufficient speed that information can be fed back into reactor performance. This is most obviously of value for reactors that run continuously, as the plasma status could be monitored and adjusted with input from the diagnostic systems. However, even reactors that function on a punctuated fashion with repetitive fusion shots could benefit from diagnostic feedback systems. Imperfections in a preceding shot could help inform reactor adjustments for the subsequent shot. Advanced measurement and feedback systems could be used to tame some instability modes.

7 NON-ENERGY APPLICATIONS

7.1 Spacecraft propulsion

NASA asked JASON to consider whether novel schemes for achieving compact, low-cost fusion power, such as those supported by the ARPA-E ALPHA program, might be adapted to the needs of spacecraft power or propulsion. Among the obvious advantages of controlled fusion for NASA's mission are:

- high fuel energy density, and therefore a high payload fraction if used to achieve high specific impulse for interplanetary flight;
- relatively low levels of radioactivity at launch from Earth compared to fission fuels

A further potential advantage suggested by Dr. Ronald Litchford in his brief to JASON is reduced exposure to solar energetic particles and cosmic rays resulting from shorter mission durations. But this must be balanced against exposure to radiation from the nuclear reactions on board.

Regarding the first advantage listed above, the theoretical energy density of deuterium-tritium fusion (hereafter "DT fusion") is $\eta_{DT} \approx 3{\times}10^{14}$ J/kg, or 0.0037 c^2, as compared to $1.6{\times}10^{7}$ J/kg for chemical combustion of hydrogen and oxygen. This is, however, only four times larger than the theoretical energy density of ^{235}U fission, $8.3{\times}10^{13}$ J/kg = 0.00093 c^2, and whereas fission reactors—even space reactors—are essentially a solved problem, the same cannot be said of fusion reactors.

These theoretical estimates neglect the ancillary mass of shielding, radiators (to reject heat), pumps, pipes, turbines, and structural materials needed by an actual power or propulsion system (the "balance of plant"). Nor do they allow for thermodynamic losses in the conversion of heat from the nuclear reactions to mechanical or electrical work (Carnot efficiencies).

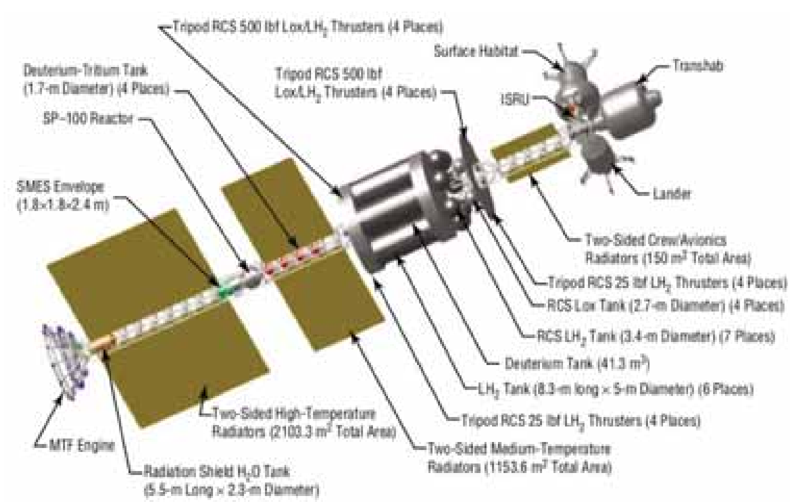

Figure 13. HOPE spacecraft design.

7.1.1 Comments on a conceptual design for a fusion-propelled spacecraft

A NASA technical report by Adams *et al.* presents notional designs of spacecraft for manned missions beyond the orbit of Mars.[59] By way of example, they detail a 654-day round-trip between Callisto (the outermost Galilean moon of Jupiter) and the L1 point of the Earth-Sun system. Their fiducial design (Fig. 13) combines magnetized-target fusion (hereafter "MTF") for propulsion with fission for electrical power. It has a total mass of 645 metric tonnes (T), of which 164 T is payload—the crew, their quarters, associated consumables, etc. The "dry" mass of the MTF propulsion system is 116 T; about half of this is shielding to protect the crew from fusion neutrons. The propellant, 106 T, is ordinary hydrogen (^{1}H); the mass of DT and DD fuel is reported to be 1/17 of this (≈ 6 T). If the fuel were burned completely and its energy converted entirely to the kinetic energy of the exhaust, the specific impulse[60] would be $I_{sp} \approx 17(2\eta_{DT})^{1/2} \approx 2.6 \times 10^6$ s. Since the reported specific impulse is only I_{sp} = 70,400 s, the net efficiency of the proposed propulsion system is ≤ 3% in terms of thrust, and the square of this in terms of energy. Part of the loss is due to neutrons, which carry off 3/4 of the energy of the DT reaction but provide negligible net thrust.[61] The rest of the discrepancy is presumably explained by incomplete burning of the fuel.

And yet this design is optimistic. The proposed MTF propulsion design involves injecting and compressing a magnetized field-reversed configuration (FRC) via plasma jets that are not distributed over a full sphere, in order to leave some solid angle free for the products to escape as exhaust and provide direct thrust (Fig. 14). It is far from clear that an FRC plasma can be stably compressed sufficiently to achieve fusion even in a more symmetrical configuration, as might be attempted for a terrestrial MTF power plant, let alone with the less symmetrical arrangement proposed for this thruster. Among other concerns, the hydrogen liner has lower molecular weight than the DT and DD fuel, so that if all of these plasmas have the same entropy (i.e., the same pressures at a common temperature), then the interface between the fuel and the liner will be Rayleigh-Taylor unstable when the latter accelerates the former.

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[59] R. B. Adams, et al., "Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets", Technical Report TP-2003-212691, NASA, 2003.

[60] Rocketeers are wont to divide the exhaust velocity by the acceleration at Earth's surface: $I\mathrm{sp} \equiv V\mathrm{exhaust}/g_\oplus$.

[61] In principle, the heat generated by the absorption of neutrons in the shielding could be contributed to the exhaust, but this does not seem to be done here.

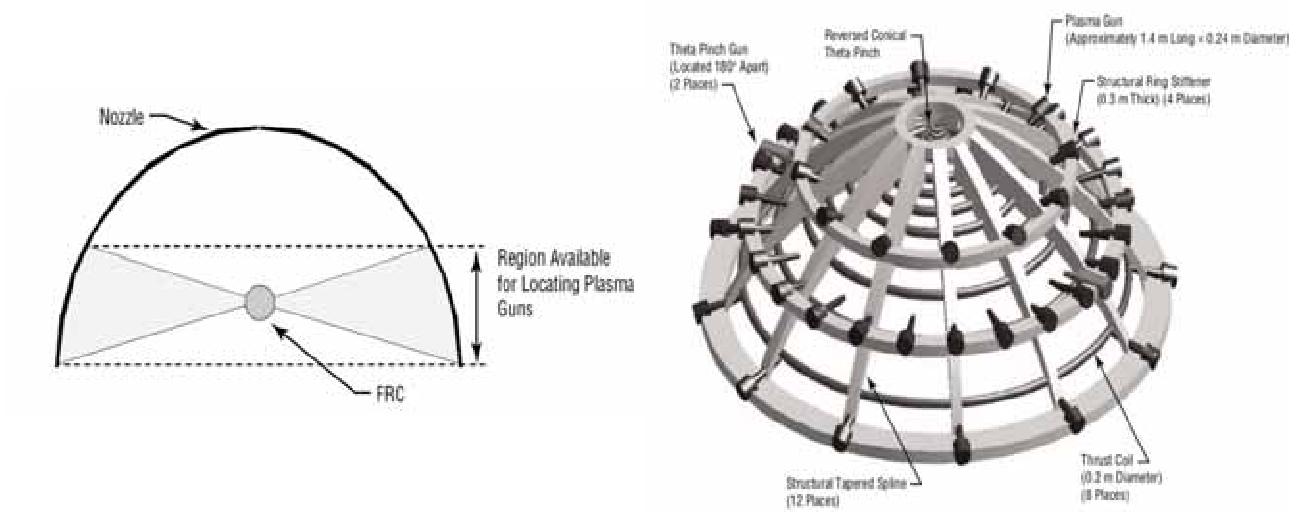

Figure 14. Distribution of plasma guns in the conceptual design of a fusion thruster. These guns inject DT plasma followed by an ordinary hydrogen (^1H) "liner" to compress the fuel and also add to the propellant mass. The gray rings in the lower panel carry current to create a magnetic nozzle that deflects and expels the expanding exhaust gases.

JASON does not wish to seem overly critical of the document by Adams *et al.*[62]. Notwithstanding the optimism concerning the fusion thruster, the overall design is admirably detailed and very instructive in illustrating the various energy losses, added weight, and complexities of a thoroughly engineered spacecraft design. For example, the design includes a 2 MW (thermal) fast spectrum fission reactor to supply 375 kW of electrical power via a Rankine cycle heat engine; thus the overall energy efficiency of the power system is 19%. The total mass of the power system is 71,370 kg, of which 90% is shielding (tungsten and lithium hydride covering a full sphere around the reactor), while 2% is for radiators, pumps, pipes, and fluid (NaK) in the heat-rejection system. It is instructive to compare this to the 100 kg initial mass in ^{235}U fuel (of which only 3.8%, or 0.005% of the total mass of the power system, is actually burned during the reactor's 50,000-hour life).

7.1.2 General physical and economic considerations

Energy densities of fuels: As the notional design discussed above illustrates, it is misleading to compare the energy densities of fission and fusion directly, since most of the mass of a practical nuclear spacecraft propulsion or power system would constitute structures and systems other than the fuel itself. But for what it's worth, the theoretical energy density of DT fuel is only four times larger than that of ^{235}U. For terrestrial commercial power production, the availability and cost of nuclear fuels, whether for fission or fusion, as well as the nature and mass of radioactive waste products, will probably be more important than the theoretical energy density. But the weight attached to these factors will probably be different

[62] R. B. Adams, et al., "Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets." Technical Report TP-2003-212691, NASA, 2003.

for spacecraft dedicated to exploration, whether manned or unmanned. Exploration of deep space is not yet a commercial venture, although it may lead to commercial enterprises eventually. For the foreseeable future, a more important economic consideration for spaceflight is the total mass that must be launched from the Earth's surface (probably by chemical rockets: see below) in order to deliver a given payload to the destination (and return the crew to Earth, in the case of a manned mission).

Shielding: Shielding is an important or even dominant part of the mass of a nuclear power plant. In a previous but unpublished study,[63] JASON suggested that a fission reactor be placed on a separate spacecraft from the crew quarters (or other sensitive payload), and that the two be connected by long cables or microwave beams for power transmission. For the purposes of the following discussion, however, we will assume that the reactor and the crew are separated by R = 100 m, which might be possible on a single spacecraft. The MTF thruster in the notional design discussed above would have a thermal power P ≈ 2 GW_{th}. If this were produced entirely by DT fusion[64], the unshielded fluence of prompt neutrons would be

$$\dot{\Phi} = \frac{\mathrm{P}}{4\,\pi\,\mathrm{R}^2 \times 14.1\,MeV} \approx 3 \times 10^{11} P_{GW} R_2^{-2} \text{ neutrons cm}^{-2}\text{s}^{-1}$$

where PGW is the thermal power in gigawatts, and R_2 the distance from the reactor divided by 100 meters. This corresponds to a radiation dose of[65]

$$H = 5 \times 10^{9} P_{GW} R_2^{-2} \text{ Sv yr}^{-1} \ .$$

The reactor shielding must reduce the dose to ∼ 1 Sv yr−1, which is at least ten times the recommended safe dosage for humans, but comparable to the unshielded dosage rate from cosmic rays and solar energetic particles outside the Earth's atmosphere. We presume that the crew quarters will have additional shielding sufficient to deal with the cosmic rays.[66]

Suppose the shielding is composed of lithium hydride (LiH), using the less common isotope ^{6}Li because of its huge cross section for absorbing low-energy neutrons and breeding tritium [^{6}Li(n,α)t]: $\sigma \approx 150(E_n/1\text{eV})^{-1/2}$ barn for $E_n \leq 10$ keV.[67] The cross-sections of ^{6}Li and ^{1}H for 14-MeV neutrons are 0.69 barn (almost entirely elastic) and 1.45 barn (67% elastic), respectively,[68] so a grammage of 125 g/cm^2 of the hydride, corresponding to a thickness of 1.73 m at room temperature, is needed to decrease the fluence of the fast neutrons by a factor 10^{-10}. Since they lose about a third of their energy in each elastic collision,

[63] "Interplanetary Travel: Nuclear Propulsion Prospects." JASON Technical Report, *JSR-01-0752*, 2001.

[64] In fact, the design calls for a combination of DT and DD fusion, in unstated proportions.

[65] J. D. Cossairt and K. Vaziri. "Neutron dose per fluence and weighting factors for use at high energy accelerators." *Health Physics* **96**, 617–628 (2009)

[66] The grammage in shielding required to block charged particle such as cosmic rays may differ from what is required to block the same fluence in neutrons, depending on the shielding material. On the other hand, inasmuch as the shielding must reduce the neutron fluence by a factor ≥ 10^{10}, only a 10% increase in the thickness and mass of the shielding would be needed to decrease the dosage by another order of magnitude.

[67] D. Steiner and M. Tobias. "Cross-section sensitivity of tritium breeding in a fusion reactor blanket: effects of uncertainties in ^{6}Li, ^{7}Li, and ^{93}Nb." *Nuclear Fusion* **14,**153 (1974).

[68] H. M. Fisher. *A Nuclear Cross Section Data Handbook*. LANL, 1989.

and since $\sim \ln(10^{10})^2 \approx 46$ scatterings are needed to random-walk across the shielding, the scattered neutrons will be moderated down to thermal energies and captured by the ^{6}Li.

The total mass of this shielding depends upon the area that needs to be covered. The MTF thruster envisaged by Adams et al. is 13 meters in diameter; if all of this needed to be shielded by a disk of the same diameter, the mass would be 166 T (about a quarter of the mass of the spacecraft). However, in MTF fusion, the neutrons are released when the target is maximally compressed and therefore much smaller than the reaction chamber; if it could be assured that the target were always close to the spacecraft axis when it burned, a considerably smaller disk diameter and mass would be sufficient to shield the forward sections of the spacecraft from the neutron flux. In fact, the design uses a tank of H_2O 2.3 m in diameter and 5.5 m long, with mass 37 T, to shield the thruster; this is 25 mean-free-paths thick, approximately the same as for our lithium hydride.

Suppose one were to dispense with the MTF drive (which one does not yet know how to build) in favor of a scaled-up fission reactor to be used for propulsion as well as power. As noted above, there would be only a modest penalty in fuel mass, but what about shielding? For the same power level, the neutron fluence of ^{23}[69]U would be somewhat lower than for DT fusion.[5] Fission also produces gamma rays: approximately 15 MeV per fission if both prompt and delayed gamma rays (the latter from beta decays of fission products) are counted. The quality factor, or biological harm per unit energy absorbed in the body, is an order of magnitude smaller than for fast neutrons. So we may assume conservatively that the required attenuation factor for fission gamma rays is comparable to that for DT-fusion neutrons at the same power level. Gamma rays with energies of 1-2 MeV are hardest to stop since, especially in a high-atomic-number shielding material, photoelectric cross sections rise rapidly toward lower photon energies, and pair-production cross sections at higher energies. The mass attenuation coefficient length is about $0.05\ \mathrm{cm}^{-2}\ \mathrm{g}^{-1}$ at 1.5 MeV in most materials,[70] so $\sim 0.46\ \mathrm{kg\ cm}^{-2}$ of shielding would be required for 23 attenuation lengths.

The total mass of shielding depends of course on the area that must be covered. Here fission reactors are at a disadvantage compared to MTF fusion ones: the active volume is much larger. Suppose for example a total thermal energy of $E_R = 1\mathrm{GW_{th}}$ yr must be produced at a burnup fraction of 3.8%: the required mass of ^{235}U is about 10 T (10^4 kg), and the corresponding volume would be 2.6 m^3 assuming a 20% volume filling fraction for the fuel. This could be accommodated in a cylinder of approximately 1 m radius and equal height. If shielding needs to be applied only in the direction of the payload, the required mass would be ~ 13 T, scaling approximately as $[E_R/(1\mathrm{GW_{th}}\ \mathrm{yr})]^{2/3}$. So at this "design point," the mass of fuel plus shielding is 23 T, to which would have to be added the mass of the reactor vessel and control rods, cooling fluids, pumps, turbines, and radiators to make a full power system; and electrically powered thrusters for propulsion. Assuming conversion of thermal to electrical power with 25% efficiency, the mass-to-electrical power ratio would therefore be $\geq 1\ \mathrm{kg/kW_e}$. Although it has not yet launched a space reactor (the Soviets and Russians have), NASA and collaborators at the national labs have designed several

[69] Each fission releases 202.5MeV and 2.5*neutrons*, but one is of these is used to sustain the chain reacton, hence there is effectively □ 135MeV of thermal power per neutron produced, as compared to □17.4 MeV for DT fusion.

[70] D. R. McCalister. "Gamma Ray Attenuation Properties of Common Shielding Materials." Technical Report, PG Research Foundation, Inc., 2013.

space reactors and even built some prototypes, most recently the kilopower reactor.[71] Some NASA employees, at least, project that reactor+shielding masses as low as 10 kg/kW$_e$ and suitable for manned missions could be achieved within 10 years, and 2 kg/kW$_e$ within 30.[72] This is in line with the lower bound estimated here, but it seems that there is a long way to go technologically.

7.2 Stockpile Stewardship

Could progress toward low-cost MIF also support the National Nuclear Security Administration (NNSA) mission? Fusion-for-energy research coexists with the stockpile stewardship activities on the NIF at Livermore and on the ZR machine at Sandia. The physical parameters of MIF plasma are unlike those in a fusion weapon, so the plasma itself is unlikely to be useful to NNSA. However, JASON identified two ways in which progress toward MIF could support the NNSA mission.

7.2.1 Pulsed neutron generation

Neutron sources are a powerful tool for studying material properties, and in pulsed mode can be used for energy-resolved mapping (via time-of-flight measurements) and for stroboscopic imaging. The potential for an ICF system to provide a pulsed neutron source that is orders of magnitude brighter than current sources has been previously explored.[73]

All MIF systems operate in a pulsed mode and therefore make pulses of neutrons. If all the matter involved is plasma (excluding machines in which plasma is compressed by liquids or solids) then these pulses will have the same duration as the period of peak plasma temperature and density. Table 5 gives the radius and lifetime at maximum compression for the MIF approaches studied by JASON. In combination with the yield, these parameters determine the fluence of the neutron source. For example, a 140 MJ D-T thermonuclear yield would produce 5×10^{19} neutrons at 14.1 MeV. For comparison, the attributes of different neutron sources are reviewed in Ref. 74. Neutron yields from small plasma focus devices are 10^9 DD neutrons, or 5×10^{10} DT neutrons if an equimolar DT gas fill is used[75]. Larger plasma focuses produce yields as high as 10^{13} DD neutrons, or 5×10^{14} DT neutrons[76]. Large spallation neutron sources have been built at Argonne (Intense Pulsed Neutron Source, decommissioned in 2008) and Oak Ridge (Spallation Neutron Source) national laboratories with neutron fluences of $\sim 4 \times 10^{16}$ n cm^{-2} s^{-1}. A MIF-based source would have ~100-fold higher fluence, but would also have longer pulse durations due to the slower implosion compared to ICF.

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[71] M. A. Gibson, S. R. Oleson, D. I. Poston, and P. McClure. “NASA’s kilopower reactor development and the path to higher power missions.” In *2017 IEEE Aerospace Conference*, pages 1–14, March 2017.

[72] M. Houts. “Space Reactor Design Overview.” ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150021391.pdf, 2015. retrieved 6/24/2018.

[73] A. Taylor, et al. "A route to the brightest possible neutron source?" Science **315** 1092-1095 (2007).

[74] L. J. Perkins, et al. "The investigation of high intensity laser driven micro neutron sources for fusion materials research at high fluence." *Nuclear fusion* **40**, 1 (2000).

[75] R. Verma, et al., "Development and characterization of a high yield transportable pulsed neutron source with efficient and compact pulsed power system." *Review of Scientific Instruments* **87,** 095102 (2016).

[76] A. Bernard, et al. "The dense plasma focus—A high intensity neutron source." *Nuclear Instruments and Methods* **145**, 191-218 (1977).

We suggest two applications:

1. Simulation of hostile environments produced by nearby exo-atmospheric nuclear explosions. Depending on the mixture of D and T used, one could simulate any desired ratio of higher energy (14 MeV) and lower energy (2.45 MeV) neutrons. At comparatively low neutron fluences the validity of neutron transport calculations in complex structures could be tested. At higher neutron yield (one proposal has suggested yields as high as 5×10^{19} neutrons) the fluences of real hostile environments might be simulated, fully testing calculations of effects.

2. Measurement of neutron scattering cross-sections, including partial inelastic cross-sections. A short-pulse monoenergetic source would enable precise determination of the energy of scattered neutrons from their post-scattering times of flight. A suitably triggered high neutron-flux system could also be used for neutron imaging of dynamics processes, such as might occur during an explosion.

Neutron scattering is used in a wide variety of other material science applications, including studies of battery technology, protein dynamics, and catalysis, and thus a MIF-based pulsed neutron source would find broad utility.

7.2.2 Tritium production

Tritium in thermonuclear weapons must be restocked to compensate for radioactive decay (half-life 12.3 years). Publicly available information puts this demand at 2.2 kg/year for the ~10,000 weapons in the U.S. arsenal,[77] but there is serious concern about the robustness of the US tritium supply.[78]

A 40 MW_{th} DT fusion reactor would consume ~2.2 kg tritium/year. For any reactor to be self-sustaining, it must breed at least as much tritium as it consumes. A 2011 JASON report analyzed in detail tritium breeding in a prospective fusion reactor, and concluded, "A 2.5 GW_{th}, 1 GW_e fusion plant with [tritium breeding ratio] TBR = 1.10 and 33% efficiency for converting heat to electrical energy, would produce about 17 kg y^{-1} of tritium beyond the 170 kg needed to replace what must be burnt."[79] At \$0.05/kWh_e, the value of the electricity from this notional plant would be $\$4.4\times10^8$ yr^{-1}. The current market cost of tritium is ~US\$30,000/g, implying a value of $\$5.1\times10^8$ yr^{-1} for the excess tritium.

While the prices of tritium and its decay product ^3He would certainly change in the face of such a dramatic increase in supply, the above estimates show that tritium production could be an important contribution to the economics of any future MIF reactor, and that emergence of MIF reactors could have implications for stockpile stewardship.

[77] https://ieer.org/resource/reports/tritium-environmental-health-budgetary-strategic-effects/#(11) (accessed 30 Oct. 2018)

[78] https://www.defensenews.com/opinion/commentary/2017/03/06/commentary-the-looming-crisis-for-us-tritium-production/ (accessed 30 Oct. 2018)

[79] JASON report JSR-11-345, "Tritium" (2011), https://fas.org/irp/agency/dod/jason/tritium.pdf

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8 MORE BANG FOR THE BUCK: COST-DRIVERS FOR MIF DEVELOPMENT

JASON was tasked: "As applicable, assess the additional time, funds, and/or specific technical investments necessary to realize low-cost magneto-inertial fusion." There are multiple steps along the way to "realize low-cost magneto-inertial fusion," principally:

- Concept exploration and computational modeling (current status of all projects)
- Break-even-equivalent conditions with D-D fuel
- Reaction and transport studies with D-D fuel doped with T
- D-T proof-of-concept
- Reactor prototype

To inform this analysis, we surveyed briefers on their capital and operating budgets, and on their wish lists for future resource allocation (See Appendix C for survey questions). Several themes emerged:

- At the present levels of ALPHA support (< $5M over three years), teams mostly work on individual components; or if a facility is already in place then the teams worked on incremental advances of pre-existing concepts. Continued funding at this level could support computational analyses that might help winnow the field of potential approaches, e.g. Ref. 80.
- The power sources themselves are a substantial, but not dominant part of the hardware costs. Typical estimates for pulsed electric power are ~$1/J, and MIF systems will require at least 10 MJ per shot for scientific break-even, and several tens of MJ/shot to approach powerplant-relevant gain. Estimates of minimum input energy are necessarily uncertain because for most approaches these estimates extrapolate across orders of magnitude in density and temperature (Fig. 10).
- Most published costing estimates for MIF focus on the hardware: the requirements for stored energy (in MCF-like devices) or impulsive peak power (in ICF-like devices). Our briefers indicated that 60-75% of their costs are for personnel, including ~20% for simulations. The hardware is only ~1/3 of the cost.
- Most MIF teams estimated that to test a new integrated concept in a D-D scale model would require ~$25 – 50M over 3 years. The projects that have reached closest to break-even-equivalent conditions had the highest cost estimates (>> $100M) to reach these conditions, while some projects in the early experimentation and planning stages estimated costs as low as $10M to reach break-even-equivalent conditions. JASON assesses that the cost estimates on the upper end of the range (>> $100M) are more realistic as they reflect the view of the most experienced teams. Cost extrapolations across orders of magnitude in conditions are unreliable.
- All briefers estimated that costs to reach scientific break-even with D-T fuel would exceed $100M; some estimated that the costs would be several $100M. While this is 'low cost' compared to NIF and ITER, it implies that unless there is a dramatic expansion in MIF research funding, there will not be federal funds available for many teams to attempt this goal. The major commercial fusion efforts all have projected costs > $450M to reach a scientific break-even D-T prototype.

[80] I. R. Lindemuth, M. R. Weis, and W. L. Atchison. "The staged z-pinch as a potential high gain fusion energy source: An independent review, a negative conclusion." *Physics of Plasmas* **25**, 102707 (2018).

Apart from MagLIF, no team has come close to scientific break-even conditions in a D-D MIF device. JASON assesses that it is too early to pick a `winning horse' in the push toward scientific break-even conditions, as the critical barriers in most approaches have not *yet* been identified. Common concerns, among the briefers and JASONs were: (1) plasma instabilities under MIF-relevant conditions and (2) liner-fuel mix (as well as removing residual liner during pulsed-mode operation in an eventual power plant). Numerical and experimental studies of these topics should be supported to develop an understanding of the fundamental requirements and constraints of MIF research. From an engineering standpoint, a recurrent theme was the need for lower cost pulsed power sources, which would need to operate at 1 Hz or faster in an eventual power plant.

JASON further recommends that a push toward scientific break-even should not be pursued for its own sake. Rather, research should focus on identifying the key technical risks for each approach, and either mitigating the risks or abandoning the approach. The configurations of the most advanced experiments, MagLIF on Z and Omega, are not suitable for power production, so further research on these facilities should focus on identifying and mitigating barriers to progress in the techniques that could plausibly be suitable for power production. This research does not necessarily require pushing to higher $n\,T\,\tau$. Rather, it could include studies of different liner materials, magnetic field configurations, or compression geometries.

Another recurring theme was the benefit of having access to expertise in simulation, plasma physics, and diagnostics; as well as access to physical tools for these activities (high-performance computing, pulsed power supplies, and measurement equipment). The national laboratories have these intellectual and physical resources in abundance. Several of the commercial and academic briefers suggested ways to help MIF efforts benefit from these resources. Leveraging the national laboratories would also help minimize redundancy of effort and equipment between MIF efforts. The **Advanced Small Modular Reactor Program**[81] and the **Gateway for Accelerated Innovation in Nuclear**[82] program were held up as models for possible future MIF efforts. Another creative idea was a federally funded externship program for National Laboratory scientists to work in academic or commercial efforts.

As the Federal Government considers its portfolio management approach to MIF, it is worth revisiting projections from a 1976 study from the Energy Research and Development Administration (the predecessor of DOE).[83] Fig. 15 shows projected time to reach a functioning MCF reactor as a function of investment. JASON has overlaid the actual expenditures on MCF and ICF in 1976 dollars, showing that the predictions of the 1976 study were remarkably prescient. JASON cautions against programmatic support that is sufficient to keep existing efforts ongoing, but is insufficient to conclusively validate or refute MIF concepts.

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[81] https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors
[82] gain.inl.gov
[83] S. O. Dean, "Fusion power by magnetic confinement," ERDA 76/110/1 UC-20, https://fire.pppl.gov/us_fusion_plan_1976.pdf

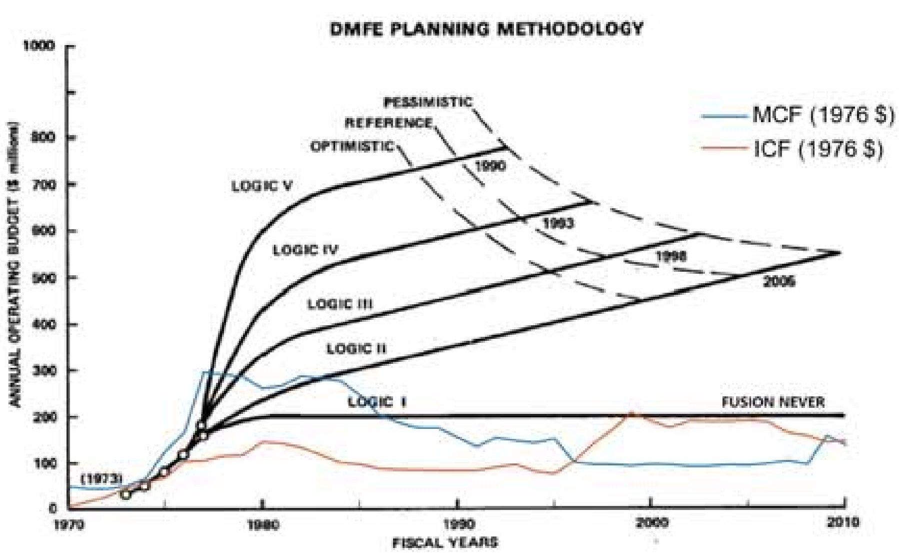

Figure 15. 1976 ERDA projections of routes to MCF fusion energy and historical fusion funding in 1976 dollars.

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9 COMMERCIALIZING FUSION

Large-scale deployment of fusion power in the US must involve commercialization, as the great bulk of generation capacity is in private hands. Although fusion is still at the "talking dog" stage (*It doesn't matter what the dog says; it's remarkable if it can talk at all!*), there is growing private-sector interest in commercializing fusion power.

9.1 The Ecosystem for Private Fusion Companies

Private investment exceeds public funding for MIF by a factor of ~10. Several private companies, some founded as early as two decades ago, have received substantial private investments to pursue the construction of commercially successful fusion reactors. JASON used open source information (news articles, corporate press releases, investor press releases) to evaluate the amounts and sources of funding received by the existing commercial fusion ventures (Fig. 16). The two oldest companies, TAE Technologies (formerly Tri Alpha Energy; > $600 M) and General Fusion (~$95 M), have secured the vast majority of the private funds invested in commercial ventures pursuing the development of high-energy fusion reactors.[84,85] Public research programs must thus account for this economic context.

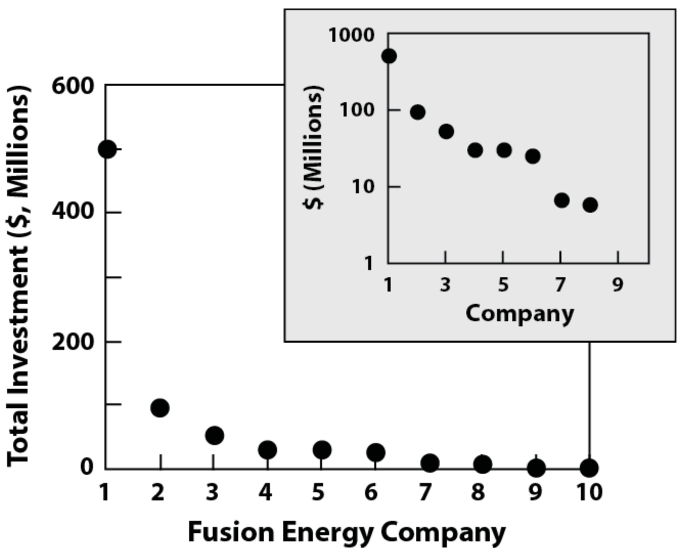

Figure 16. Total investments received by existing commercial thermonuclear fusion companies. Values were converted into $ (US) when necessary. *Inset:* data from the main graph plotted on a $\log_{10}$ scale, excluding companies with no private investment.

Private companies are performing cutting-edge research. The scale of private investment means that some private efforts are further along than academic, and by some measures, national laboratory, teams. Federal investment should thus support these efforts, provided that the federal support leads to durable and publicly disseminated learning. Federal support can come in forms other than direct grant funding, such as sabbatical programs for National Lab personnel in private companies; and access to technical expertise, computational resources, and diagnostic equipment at National Labs.

[84] https://www.geekwire.com/2018/tae-technologies-pushes-plasma-machine-new-high-fusion-frontier/

[85] https://www.geekwire.com/2018/commercial-fusion-ventures-learn-lessons-engineering-expectations/

Private R&D is often proprietary. Many components are shared between the different MIF approaches (e.g. pulsed power systems, plasma jets, diagnostics). Most commercial fusion endeavors are pursuing research only on key subsystems, or are building small-scale test reactors. Thus there is opportunity for mutual learning which should not be damped by premature competition. Federal support (of private, academic, and National Lab teams) should be contingent upon public dissemination of results to the greatest extent possible. Support for workshops and conferences provides a low-cost means to encourage information sharing. In other industries, e.g. Pharma, federal support has been used to catalyze formation of pre-competitive public-private consortia to address challenges that are beyond the capabilities of individual private enterprises, e.g.[86] Similar opportunities exist in MIF.

Private enterprise is fluid. Given the large costs and long timescales to reach a commercial fusion reactor, one can expect that there will be mergers, acquisitions, and failures in the private efforts; and that the failures may be driven by non-technical factors. These considerations further underscore the importance of supporting durable knowledge production in the private efforts.

The timescale to reach commercial fusion exceeds the 7 to 10-year timescale of many venture capital funds, suggesting that some investors' interests may not align with long-term goals. Such investors may be motivated to achieve key milestones that lead to an increase in perceived value and liquidity, regardless of whether these milestones genuinely advance the effort; others may redirect resources toward ancillary uses of fusion technologies (e.g. particle-beams for materials processing and medical applications.) Federal support for commercial MIF efforts should thus focus on building a solid foundation of technical work that will apply to multiple efforts.

In a recent article,[87] one major VC supporter of fusion R&D (Venrock) clearly details their rationale for funding an endeavor that is considered to be a much longer term investment than normal. Other investors, such as sovereign wealth funds, can accommodate the necessary decadal timescales.

Investors vary in sophistication. Fusion is sufficiently complex that many investors will not be able to perform adequate technical diligence on novel approaches. For instance, a cold fusion company called Industrial Heat recently attracted substantial investment (~$42 M),[88] despite being based on a discredited approach. Backlash from unsuccessful efforts or over-inflated claims can damage the whole industry. Federal investment should support the establishment of industry standards and independent verification of fusion-related claims. For instance, diverse definitions of 'scientific break-even' are in common use, leading to ambiguous claims. Adoption of standard diagnostics e.g. for neutron production, will help facilitate quantitative comparisons between approaches.

Investors often flock together. A corollary to the challenge of independently verifying technical merits of a MIF effort is the impulse to `bet on a winning horse' and to invest in the perceived front-runner of the moment. This impulse can drive an instability in the investment ecosystem, concentrating resources in projects that are not necessarily the best long-term prospects. This private dynamic mirrors the dynamic in federal support, e.g. concentrated MCF research on tokomaks, possibly to the exclusion of other viable approaches.

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[86] Volkow, N.D., and Collins, F.S. "The role of science in addressing the opioid crisis." New England Journal of Medicine **377.4**, 391-394 (2017).

[87] http://issues.org/32-2/whats-the-big-idea/

[88] https://ftalphaville.ft.com/2016/11/25/2180322/so-neil-woodford-invested-in-a-cold-fusion-company/

Just as JASON advises against concentrating federal resources too early in the technology development, JASON also advises against federal funding strategies that could trigger private concentration of investment. ALPHA funding has the greatest positive impact on the smallest commercial entrants. Indeed, ARPA-E grant support appears to be an important source of funding for three of the newest representatives (Helion; MIFTI; NumerEX) of this small but ambitious community. Since fusion-relevant conditions are still a distant hope for all commercial efforts, JASON recommends that all technically plausible efforts be supported for as long as possible (with an emphasis on identifying failure modes). By ensuring rigorous technical review and adherence to community-wide standards, ARPA-E has the opportunity, through its funding decisions, to provide unbiased validation that investors can use in their decision-making.

A recurring theme from the commercial efforts was the challenge of finding appropriately trained employees. Individual careers will likely span many commercial efforts, so investment in fusion-related workforce development is likely one of the highest-impact opportunities.

9.2 Commercialization Challenges

As discussed in Chapter 2, the economics of electricity generation are complicated. A simple figure such as a projected levelized cost of energy from a particular plant design is insufficient to predict the commercial viability and adoption of that technology. Additional challenges are:

- **Fusion must not only work, but must be better:** There is no fundamental shortage of primary energy resources that might motivate a search for a new fuel source. Further, there are many generating technologies and generators on the grid and the value of electricity to the end-user is independent of how it is generated. For fusion to be commercially viable, not only does it have to "work", but it must be "better" than the alternatives in one or more dimensions. Among those are operational flexibility, reliability, environmental impact, proliferation impact, the balance of capital/operating costs, and non-technical factors such as public acceptance, aesthetics, or technological prestige.
- **Utilities are technically conservative:** The primary goal of private utilities is to make a profit, while that of public utilities is to serve their customers reliably at the lowest cost. Technological innovation is a low priority.
- **Large investments are involved:** Like fission, fusion is expected to be capital intensive (fission is currently some $6-8/Watt overnight cost, compared to NGCC, which can be less than $1/Watt). As a result, investments are long-term, with attendant risks and low (utility-level) rates of return.
- **Fusion technology will be regulated** because of the safety aspects of tritium, neutrons, and activated materials. Further, as the neutrons from a fusion facility could also be used to create weapons-usable materials (e.g., breeding ^{239}Pu by adding ^{238}U to the blanket), non-proliferation considerations will favor Federal, if not international, regulation.
- **US electricity demand is projected to be growing slowly** through 2040 relative to historical norms, with electricity intensity falling in all sectors due to efficiency improvements.[89] Additions to generating capacity are projected to average some 15 GW per year through 2040, with the mix evolving due to

[89] https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf

changes in taxation and regulation. Growth in electric vehicle adoption introduces uncertainty, but accounts for a relatively small contribution in the EIA projections (ca. 1 million annual EV sales by 2030) that would not substantially change the overall demand outlook even if doubled. In contrast, electricity demand and generating capacity additions are expected to continue growing strongly in non-OECD countries. For that reason, as well as a less-restrictive regulatory environment, it is likely that the first power-producing fusion plant, if one is ever built, will be located outside of the US.

- **The periphery of the grid is evolving most rapidly**. This evolution is driven by declining costs of photovoltaics, electric vehicles and energy storage, along with the capability of power electronics and information technology to coordinate and control distributed resources and loads. Microgrids can assure power quality and reliability with less dependence on central generation and transmission resources, increasingly within economic reach. The role of the electric utility itself is evolving, with new actors such as "prosumers" and aggregators taking the regulatory and policy stage. California is mandating Zero Net Energy residential construction as of 2020. This context calls into question the overall size of the bulk power generation market in which fusion would aim to compete.

This multiplicity of challenges means that some form of government support will be required to enable commercial deployment of fusion power even after demonstration of technical feasibility.

9.3 Lessons from Fission

It is useful to consider what happened in the case of nuclear power,[90] the first time the government tried to catalyze deployment of a novel, capital-intensive generating technology. The current challenges faced by the U.S. nuclear industry suggest that Federal support of fission development could have been better managed.

Following the creation of the first man-made reactor by Fermi *et al*. in late 1941, reactors were developed and used in the Manhattan Project to produce plutonium for nuclear weapons. The Atomic Energy Act of 1946 set civilian nuclear energy as a federal policy goal and enabled power reactor progress via Atomic Energy Commission (AEC) support, culminating in the first order for a privately-financed full-scale commercial reactor at Oyster Creek, whose construction began in 1964. Simultaneously, the US government was pursuing nuclear reactors for naval propulsion beginning in the late 1940s, culminating in the launch of the USS Nautilus submarine in late 1954. There are today some 100 nuclear reactors producing 19% of US electricity and in 2017, 81 U.S. naval ships[91] (11 aircraft carriers and 70 submarines – 18 SSBN/SSGN and 52 SSN) were powered by 92 reactor cores.

The US government took a number of important steps to facilitate the development and deployment of nuclear power in the early years. Quoting from the report, these included:

- ***Atomic Energy Acts of 1946 and 1954:*** *The AEA of 1946 established the AEC and set federal policy for civilian use of nuclear energy, including the explicit use of nuclear power for commercial reactors, however retained significant federal control over access to fissile materials, research data, and*

[90] https://www.energy.gov/sites/prod/files/2017/01/f34/Innovation%20Pathway%20Study--U.S.%20Commercial%20Nuclear%20Power.pdf

[91] http://www.world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx

intellectual property. The AEA amendments of 1954 loosened these restrictions and directed AEC to begin licensing privately-owned power plants.

- ***AEC R&D:*** *AEC R&D policies, programs, and funding created the basic scientific understanding of how to build a uranium-fueled fission reactor, control the reaction, and extract usable heat that could be used to generate electricity. After the 1954 AEA amendments, the Civilian Application Program (CAP) enabled the transfer of AEC and DoD research to private sector companies for use in commercial development of reactors.*
- ***AEC Demonstration Programs:*** *Following the AEA amendments of 1954, AEC implemented the Power Reactor Demonstration Program (PRDP) to encourage utilities to partner with prospective NSSS manufacturers and AEC in order to gain crucial construction and operational experience. The PRDP played a significant role in identifying the commercial readiness of various reactor technologies and provided GE and Westinghouse with sufficient confidence to offer commercial reactors.*
- ***Price-Anderson Act:*** *The 1957 law was intended to reduce liability risks associated with commercial nuclear power plants by setting a maximum liability for plant owners in case of accidents, above which the federal government would pay damages. The act was intended to temporarily address the inability of utilities to obtain insurance, however it has been continually extended and updated.*

There are, however, several crucial differences between today's fusion situation and the early fission situation:

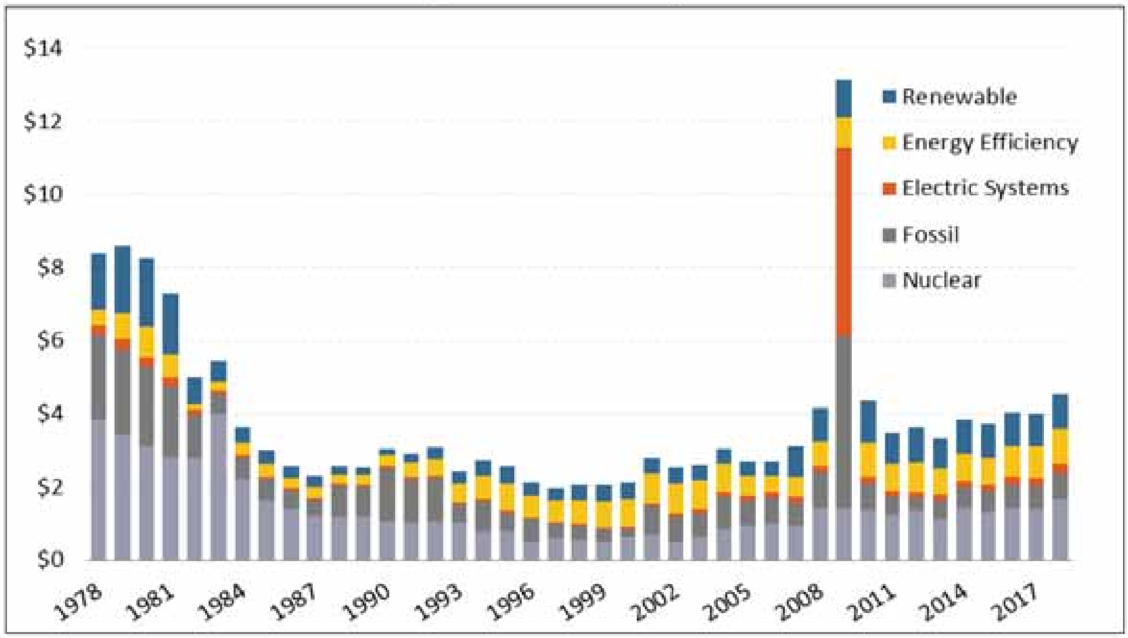
- Reactor progress was, and continued to be, driven by national security needs (nuclear weapons, naval propulsion), and later national prestige. Civilian nuclear power was a spin-off of those other efforts, which had very different design constraints.
- Reactors had already been demonstrated when the push to commercial power began.
- Some of the reactor technologies and most of the fuel technologies were closely held by the US government.

9.4 Lessons from Wind and Solar

The commercial evolution of wind and solar electric power generation technologies is another point of comparison. As with nuclear fission and fusion, these renewable resources offer a primary energy supply that is practically unlimited and that would remain viable under severe constraints on carbon emissions. And likewise, the development and deployment of renewable resources has been driven by governmental policy and incentives. Federal investment in wind and solar R&D was most significant during the earlier development stages, although substantially smaller than R&D funding for fossil and nuclear energy over the past seven decades, as shown in Figure 17.[92]

[92] Corrie Clark, *Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, Energy Efficiency, and Electric Systems R&D.* Congressional Research Service Report RS22858, June 2018. https://fas.org/sgp/crs/misc/RS22858.pdf

Figure 1. Fiscal Year R&D Funding of DOE Energy Technologies
(billions of 2016 dollars)



Source: *DOE Budget Authority History Table by Appropriation*, May 2007; *DOE Congressional Budget Requests* (several years); Deflator Source: *The Budget for Fiscal Year 2019*. Historical Tables. Table 10.1. Gross Domestic Product and Deflators Used in the Historical Tables, 1940-2023.

Notes: Column for FY2009 includes funding provided in the American Recovery and Reinvestment Act of 2009 (P.L. 111-5).

Figure 17. Fiscal Year R&D Funding of DOE Energy Technologies, from Clark/CRS 2018.

Subsidies now largely consist of production tax credits on a path toward phase-out, with a marked drop since 2013.[93] Other incentives for wind and solar deployment include renewable portfolio standards at the State level. In 2016, wind accounted for 5.6% of electric energy generation in the U.S. and solar thermal and photovoltaic ca. 1.3%.[94] As of early 2018, wind contributed ca. 8% to U.S. electricity generation,[95] with an installed capacity of 90 GW[96]. Installed nuclear had a roughly similar capacity, but contributed more (~19%) of U.S. grid electricity due to the higher duty cycle of nuclear plants vs. wind.

Wind and solar power are only now playing a transformative role in global energy, after a long history of serving in niche applications and finally being tailored for mass markets through additional decades of R&D. Aerodynamic lift has been understood for many centuries of sailing, and wind electricity generation was demonstrated in the 1880s. The photovoltaic effect was observed in the 19th century, and PV cells have been used for space applications since the 1950s. Solar thermal power uses well-understood

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93 *Direct Financial Interventions and Subsidies in Energy in Fiscal Year 2016.* U.S. Energy Information Administration, April 2018. https://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf

94 https://www.eia.gov/electricity/annual/html/epa_01_01.html . Note that solar generation is difficult to estimate both due to annual growth in the tens of percent, and the large contribution from customer-owned rooftop photovoltaics that are not captured by electricity sales data.

95 https://www.eia.gov/totalenergy/data/monthly/pdf/sec7_6.pdf

96 American Wind Energy Association U.S. Wind Industry Second Quarter 2018 Market Report https://www.awea.org/2018-market-reports

thermodynamics much like a fossil-fuel plant. The interesting and important innovations for all of these technologies have centered on fine points: marginal improvements in performance and practicality through clever design and new materials, but not the application of new principles from a little understood branch of physics. Efficiencies were increased by single digits at a time, over many iterations. This home stretch of development and commercialization has taken longer than many in the industry anticipated: a common joke held that photovoltaics are exactly seven years from being cost-effective – and have been so for decades. Though the pattern finally broke for renewables, the analogous joke for fusion, where the time constant is closer to 30 years, gives one pause.

Arguably, the history of alternative energy commercialization – for renewables as well as nuclear – can only be understood within a political-economic context that accounts for industry lobbying, public opinion, and other forces beyond the purview of engineering economics or scientific forecasting. For example, a budding industry of wind electricity generation on U.S. farms in the 1930s was stalled by rural electrification, a highly subsidized effort to provide equal access to a reliable grid. The simple, general lesson is just how much stands between scientific demonstration and a successful commercial product.

Some specific observations:

- Technological progress benefits from iterations along a learning curve. This is helped by smaller-scale, repeatable units of hardware.
- Manufacturing economies of scale are important. This also favors smaller, repeatable units. Nevertheless, optimal unit scale is not obvious from the outset. The history of wind power development has seen trend reversals, first toward larger, then smaller, then larger machines with new design solutions for problems associated with large diameter rotors. Photovoltaics, a paradigm of modular technology, are being deployed in large commercial arrays often comprising tens of thousands of modules.
- Like the nuclear industry, the manufacturing of wind and solar generation technology is global: China produced 70% of PV modules in 2017, North America 3.7%.[97] The two leading producers of wind turbines are European.[98] The policy question of what R&D strategy the U.S. should pursue with respect to energy technology is linked to the question of what international role the U.S. wishes to play.
- The deployment of renewable generation has not followed a straight path of engineering-economic cost minimization. On the one hand, some technically promising opportunities to exploit lowest-cost resources such as offshore wind and solar power in fragile deserts have been put aside due to environmental concerns and “not-in-my-backyard” opposition; being “green” does not guarantee easy project siting. On the other hand, rooftop PV is a popular favorite, despite generally higher per-kW cost than centralized solar power plants, owing at least in part to qualities such as aesthetics and cultural symbolism.

In sum, the path to a viable commercial fusion power plant, if it exists, may hold many surprises.

[97] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[98] https://www.windpowermonthly.com/article/1445638/top-ten-turbine-makers-2017

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10 FINDINGS AND RECOMMENDATIONS

The findings of this study are summarized below.

1. Magneto-Inertial Fusion (MIF) is a physically plausible approach to studying controlled thermonuclear fusion in a region of parameter space that is less explored than Inertial Confinement Fusion (ICF) or Magnetic Confinement Fusion (MCF).
2. MIF research is immature. Despite having received ~1% the funding of MCF and ICF, MIF experiments have made rapid progress in recent years toward break-even conditions, and some (e.g. MagLIF) are within a factor of 10 of ‘scientific break-even’.
3. There are many plausible and distinct approaches to MIF. Some early projects supported by the ALPHA program are showing rapid progress in critical physical parameters and have not *yet* reached insurmountable obstacles. As in ICF and MCF, instabilities may make scientific break-even MIF more challenging than simple scaling estimates suggest.
4. ALPHA program support for development of broadly applicable technologies has accelerated progress of multiple efforts. All MIF approaches would benefit from improved understanding of plasma instabilities and liner-plasma interactions, better computational tools, and improved diagnostics.
5. While scaling from current experiments is uncertain, it is likely that reaching scientific break-even with a single MIF prototype will cost at least several $100M and possibly much more. Considerably larger expenditures would be required to go from scientific breakeven to a demonstration power plant; and even more from a demo to a production capability.
6. Given the immaturity of the technologies, the future ability of fusion-generated electricity to meet commercial constraints cannot be usefully assessed. Rapidly developing infrastructures for natural gas and renewable energy sources and storage will compete with any future commercial fusion efforts. Nevertheless, there is a small but growing private-sector community investing in and pursuing commercial fusion projects.
7. The pursuit of MIF could lead to valuable spinoff technologies, and to non-power fusion applications, with broad civilian and military import. Some approaches have low enough mass to be candidates for space propulsion, but it is too early to impose the relevant design constraints (low weight, low thermal dissipation) on ongoing research.
8. MIF research could productively absorb a significantly higher level of funding than the $10M/yr of the ALPHA program.

These findings lead to the following recommendations:

1. MIF activities should be supported by an investment in basic research to:
    a. study plasma instabilities and transport under MIF conditions, and
    b. study plasma-liner interactions.
2. The National Laboratories should contribute their unclassified state-of-the-art simulation codes to collaborations with academic and commercial efforts, and support training of qualified users.
3. Targeted technology development programs should focus on development of components, including plasma guns (high Z and low Z), pulsed power and electronics, diagnostics, and advanced magnets and materials.
4. The near-term goal should be scientific break-even (thermonuclear energy out > mechanical + electromagnetic energy into the fuel) in a system which plausibly scales to a commercial plant. Until

that goal is achieved, set aside questions of neutron economy (tritium breeding) or balance of plant. Pursue system integration only insofar as it is needed to demonstrate scientific break-even.

5. Explore pulsed neutron sources and space propulsion as motivating applications with different constraints than grid electricity. Efforts in these speculative directions should supplement, not replace, basic MIF research.
6. Support all promising approaches for as long as possible. Do not concentrate all resources on early front-runners.

APPENDIX A: Statement of Work (SOW)

Background

In 2014 the Advanced Research Projects Agency, Energy (ARPA-E) announced a funding opportunity announcement known as Accelerating Low-cost Plasma Heating and Assembly (ALPHA)[99]. The stated goal of the ALPHA program was to:

> *Develop and demonstrate low-cost tools to aid in the development of fusion power, with a focus on approaches to produce thermonuclear plasmas in the final density range of 10^{18}-10^{23} ions/cm^3. The program goal is to create a toolset that will allow a significant reduction in facilities costs for fusion development and to enable rapid learning through a high shot rate at a low cost-per-shot.*

Scope

Alternative approaches to fusion (for energy, propulsion, or security) that are distinct from the mainline approaches of (a) short-pulse inertial fusion (density $\geq 10^{23}$ ions/cm^3, as at the National Ignition Facility) or (b) long-pulse, magnetically confined fusion (density $\leq 10^{18}$ ions/cm^3, as in the multinational ITER project).

The ALPHA program kicked off in fall 2015 and is scheduled to wrap-up in late 2018. As the ALPHA program approaches completion, have the nine ALPHA teams realized the goals of ALPHA? What have we learned? Which additional challenges remain for the ALPHA teams and the larger magneto-inertial fusion community? What's needed next?

Objectives

1. Survey the progress of magneto-inertial fusion teams both inside and outside of ALPHA toward their stated goals.
2. Assess the progress of ALPHA and non-ALPHA magneto-inertial fusion teams toward realizing low-cost fusion.
3. As applicable, assess the additional time, funds, and/or specific technical investments necessary to realize low-cost magneto-inertial fusion. Particular topics of interest include scientifically-credible opportunities to cost-effectively reduce *technical* and *schedule* risk in pursuit of fusion applications.

[99] https://arpa-e-foa.energy.gov/Default.aspx?Search=alpha&SearchType=#FoaId4c902711-2bf4-409d-bd46-8d9c57ed83d1

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APPENDIX B: Briefings

ARPA-E/NASA The Promise of Low-Cost Fusion Development: Methods to accelerate low-cost plasma heating and assembly

AGENDA
June 11-12, 2018

MONDAY, 11 JUNE

Time	Title	Speaker	Classification
0900-0910	**Welcome**	JASON	U
0910-0940	**Introduction & ARPA-E Perspective**	Patrick McGrath	U
0940-1010	**NASA Perspective**	Ron Litchford	U
1010-1020	**Break**		
1020-1120	**Overview of Magneto-Inertial Fusion**	Scott Hsu	U
1120-1220	**MIF Research on Z and Relevant Classification Guidance**	Daniel Sinars	S/RD
1220-1320	**Lunch**		
1320-1420	**Z-pinch Concepts Review**	Farhat Beg	U
1420-1520	**Laboratory for Laser Energetics**	Mike Campbell	U
1520-1535	**Break**		
1535-1635	**General Fusion Program**	Michael Delage	U
1635-1700	**Wrap-Up and Discussion**	All	U

*** 1830 No-host Dinner to follow, location: Seasons 52***

TUESDAY, 12 JUNE

Time	Title	Speaker	Classification
0900-0910	**Welcome and Recap of Day 1**	Ryan Umstattd	U
0910-1010	**Spherically Imploding Plasma Liners Formed by Merging Hypersonic Plasma Jets**	Scott Hsu	U
1010-1025	**Break**		
1025-1125	**Title TBD**	David Kirtley	U
1125-1225	**Title TBD - VTC**	Simon Woodruff	U
1225-1325	**Lunch**		
1325-1425	**Development of the Sheared Flow Stabilized Z-Pinch as a Compact Fusion Device**	Uri Shumlak	U
1425-1525	**Accelerating Development of Fusion Energy with High-Field Tokamaks**	Dan Brunner	U
1525-1540	**Break**		
1540-1640	**Title TBD**	Mike Zarnstorff	U
1640-1700	**Wrap-Up and Discussion**	All	U

In addition to these on-site briefings, four study participants made a 4-hour visit to the DIII-D Tokamak on the General Atomics Campus on Monday June 18, and six study participants made a 2-hour site visit to the Tri Alpha Energy facility in Foothill Ranch, CA on Friday, June 29.

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APPENDIX C: Briefer Questionnaire

Instructions: Please fill the table with the years of critical milestones, going back no further than 5 years, and going forward no further than 5 years (enter as many rows as you wish). Please ignore any irrelevant fields. For the highlighted fields, please enter parameters at maximum compression.

Year	Shot rate	Material consumed per shot, including vessel etc. (g)	Input energy per shot	B initial (T)	Initial temperature (eV)	Geometry (sphere or cylinder)	Convergence ratio

β	B (T)	Temperature (keV)	R (cm)	BR (G cm)	Density (ions/cm^3)	rho R (g/cm^2)

Lawson time (s)	Confinement time (s)	Neutron yield (#) (specify whether DD or DT)	Names of any software packages used in simulations	Comments

Costing questions:

Approximately how much money have you spent to-date on your system? If you used substantial repurposed items or in-kind contributions, please include estimates of their value.

What were the main categories of expenses and approximately how much went to each (e.g. pulsed power system; magnets; simulations; personnel; etc.).

What would you spend the additional money on if you had an extra $1M? $10M? $100M?

What areas of federal support, in your opinion, would best accelerate progress toward MIF break-even?

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APPENDIX D: Evaporation of Liquid Pb Liners by High-flux Neutrons

Some magneto-inertial fusion proposals involve cylindrical or spherical liners of Pb or Pb-Li alloy to compress the plasma and (if ^{6}Li is alloyed with the Pb) breed tritium. Here we estimate the maximum neutron fluence that can be tolerated without boiling the liner.

We have been unable to find values for the latent heat of evaporation of Pb-Li alloys (other thermodynamic data for Pb-Li eutectics may be found in Ref. 100. The Pb partial vapor pressure is given in Fig. 8. Raoult's law overestimates the Li partial vapor pressure of the Pb-Li eutectic by a factor of 1400,[101] indicating strong chemical binding of Li to Pb. We will consider only Pb (the eutectic is 84.3% Pb by atomic composition and 99.3% by mass), treating the alloy as if it were pure Pb. Pure Pb is less volatile than pure Li, so this is a conservative approximation.

Consider a cylindrical fusion reactor of length *l* and neutron energy yield *Y* (e.g. modeled after the Compact Fusion Systems design). The maximum radius at which the liner vaporizes is

$$r_{max} = \frac{Y\sigma_E N_A}{2\pi l\ \Delta H^{vap}} = \frac{Y/l}{5\ \text{MJ/cm}} \approx 26\ \text{cm}$$

where $\sigma_E \approx 10$ b is the energy deposition cross-section[102] for ^{208}Pb and analogous references for the other major isotopes ^{206}Pb and ^{207}Pb, N_A is Avogadro's Number and ΔH^{vap} = 1.78 kJ/mole is the latent heat of vaporization of Pb. We have neglected the enthalpy required to heat Pb to its (pressure-dependent) boiling point and the temperature dependence of ΔH^{vap}, rather roughly equated the inelastic cross-section to the energy-deposition cross-section, and have ignored the complexity of neutron scattering and energy degradation. The former approximations are not large, but the final approximation likely introduces a factor of two uncertainty into the result. $\frac{Y}{l} \approx \frac{5\ \text{MJ}}{\text{cm}}$ may be roughly appropriate for an actual power-generating reactor; experiments and even useful neutron sources may involve values smaller by orders of magnitude.

Any liner material closer to the plasma than r_{max} will boil, introducing a large quantity of neutral Pb and Li vapor into the experimental chamber in addition to that evaporated (without boiling) from the inner surface of the liner.

The Pb boils at the temperature where its vapor pressure matches the pressure inside the liquid Pb. At a depth *d* below the surface, the pressure in the liquid Pb is $P = g_{eff}\rho d$, where g_{eff} is the combination of gravitational and centripetal acceleration of the lead and ρ is the density. When the reactor cavity is fully expanded with initial radius r_i, the initial centripetal acceleration must be $g_i > g$ to avoid collapse under Earth's gravity. As the liner collapses to final radius r_f, conservation of angular momentum implies that its linear velocity grows. The centripetal acceleration scales as $\frac{g_{eff}}{g_i} = \left(\frac{r_i}{r_f}\right)^3$. Thus for convergence ratios of 10 – 20, the final centripetal acceleration will be immense: $10^3 - 10^4$ g. At

[100] E.M. De Les Valls, , et al. "Lead–lithium eutectic material database for nuclear fusion technology." *Journal of nuclear materials* **376**, 353-357 (2008).
[101] N. J. Hoffman, A. Darnell, and J. A. Blink. "Properties of lead-lithium solutions." No. UCRL-84273; CONF-801011-9. (1980).
[102] t2.lanl.gov/nis/data/endf/endfvii.1-n-pdf/pb208.pdf

a depth d = 1 cm from its surface (the neutron energy deposition has a characteristic depth of about 4 cm) the liquid Pb will have a pressure $P = 10^6 - 10^7$ Pa and will vaporize at a temperature > 3000 K. Neutral Pb vapor would flow freely across magnetic field lines into the plasma, where it would be quickly ionized by charge exchange with plasma ions or by UV radiation. At this density it would quench any thermonuclear plasma by its rapid bremsstrahlung, bound-free and bound-bound radiation. The extent of liner penetration will depend on the rate at which the Pb atoms are heated and ionized as they intermingle with the fuel.[103]

Vaporization of the inner Pb surface will also disrupt the electrical currents which are responsible for maintaining the intense magnetic field in the plasma.

[103] P. J. Turchi, S. D. Frese, and M. H. Frese. "Stabilized Liner Compressor For Low-Cost Controlled Fusion: Progress And Issues." *2017 IEEE International Conference on Plasma Science (ICOPS)*. IEEE, (2017).

CHANGING WHAT'S POSSIBLE

JASON STUDY ON THE PROSPECTS FOR LOW-COST FUSION DEVELOPMENT

ARPA-E is grateful to JASON for conducting this study and for their insightful findings and recommendations.

Here, we provide commentary related to their finding #6: “Given the immaturity of the technologies, the future ability of fusion-generated electricity to meet commercial constraints cannot be usefully assessed…” This is a fair statement given the large uncertainties in the state of the technology and in the future needs of the U.S. and world electricity markets. However, in the view of ARPA-E, some of the analysis in Sec. 2.3 (Fusion in the Energy Landscape) does not adequately capture the full range of potential outcomes for either the technology or for the market needs.

Section 2.3 includes some analysis based upon a maximum levelized-cost-of-electricity (LCOE) of $0.05/kWh, which is drawn from the current estimate for natural gas combined cycle (NGCC) electricity generation, and leads to a rough estimate of a maximum allowable overnight capital cost of $5.55/W. This is compared against a notional $6.67/W fusion power plant from the referenced Bechtel cost study. However, the latter, which examined the cost drivers for four fusion-core concepts applied to a 150-MW point design, was intended to identify the main cost levers, not to arrive at accurate, absolute capital cost estimates for a future fusion plant. In fact, the study was based upon costing models for nuclear fission plants that are already known to be well above costs being achieved in other parts of the world. For example, Korea has repeatedly shown that present-generation fission plants can be built for roughly $2/W. Thus, conclusions drawn based on capital cost estimates from the Bechtel study could be overly pessimistic.

From the standpoint of market needs, a benchmark of NGCC in the current context of the U.S. grid does not adequately capture global markets and/or market segments where fusion might be first adopted, or the future needs of the electric grid. Benefits of fusion that do not factor into such an analysis include:

- minimal carbon emissions
- geographic siting flexibility, with a small footprint, including near dense population centers
- seasonal stability, high dispatchability, and potential load-following capability
- a practically inexhaustible fuel supply with minimal need for new transportation/delivery infrastructure.

In fairness, NGCC does address some of these considerations as well, but these features are not well captured by the $0.05/kWh LCOE figure. The JASON study does note that there are applications that can justify electricity costs well above the notional $0.05/kWh, and that the likely largest market for fusion energy may not be in the U.S. In addition, the study acknowledges that there are certain markets within the U.S. where there are income streams for ancillary services that can meet or even exceed the value of selling baseload electricity. These caveats serve to remind us that directly comparing early estimates for fusion-plant capital costs with income based on current U.S. LCOE projections for NGCC is too restrictive to assess the future market attractiveness of fusion power.

Beyond the specific details of the cost analysis, the JASON report highlights the importance of including cost analyses in assessing the potential real-world impact of fusion (or any energy technology). This is a message that ARPA-E appreciates, and we hope that the fusion R&D community will embrace this attitude as it continues to make progress.